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TCREC TECHNICAL REPORT 61-120

VOLUME IV

THEORETICAL INVESTIGATION OF DUCTED PROPELLER AERODYNAMICS

Task 9R38-11-009-12

Contract DA 44-177-TC-674

September 1961

prepared by :

REPUBLIC AVIATION CORPORATION
Farmingdale, Long Island, New York

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Task 9R38-11-009-12
Contract DA 44-177-TC-674
September 1961

THEORETICAL INVESTIGATION OF DUCTED PROPELLER AERODYNAMICS

Volume IV

by

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HEADQUARTERS
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
TRANSPORTATION CORPS
Fort Eustis, Virginia

FOREWORD

This report is one of a series presenting the results of research performed in the field of shrouded propeller aerodynamics, under contract for the U. S. Army Transportation Research Command.

The work performed by Dr. Theodorsen and his associates at Republic Aviation Corporation is presented in four volumes. The first two volumes were issued during August 1960, under Contract DA 44-177-TC-606. This volume presents a discussion of vertical take-off vehicles.

The report has been reviewed by the U. S. Army Transportation Research Command and is considered to be technically sound. The report is published for the exchange of information and the stimulation of ideas.

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VOLUME IV

CONTENTS

INTRODUCTION

In this volume certain practical VTOL developments are reviewed and discussed.

In Section A the measured performance of a fixed-pitch tilting ducted propeller VTOL aircraft throughout its speed range is analyzed in detail and compared to the ideal performance. The performance of a hypothetical configuration employing free propellers in place of the ducted propellers is then computed and compared with the ducted propeller. The ducted propellers are designed for maximum hovering efficiency, and the free propellers are standard cruise propellers, data for which were readily available. The free propellers are sized to match the hovering performance of the ducted propellers.

Section B enlarges the comparison made in Section A by presenting the performance of a hypothetical configuration using free propellers designed for maximum hovering efficiency. Data for such propellers were not available; therefore, one was designed for this purpose using the methods outlined by Lock and Theodorsen. The comparison is made on a variable-pitch constant speed basis with the free propellers sized to match the hovering performance of the ducted propellers.

Section C is an appraisal and analysis of the practical aspects of VTOL aircraft based on a survey of the existing VTOL test beds. A general summary of the design details and performance of all the vehicles is presented in graphical form which uses as parameters forward speed and hovering downwash velocity. A table containing the basic design and performance figures for each vehicle is given. The special purpose vehicles such as the flying jeeps, aerial platforms and aerodynes are treated as a separate group.

Particular performance data of the various VTOL aircraft are collected in an Appendix.

SECTION A

COMPARISON OF THE PERFORMANCE OF A TILTING PROPELLER VTOL AIRCRAFT WITH AND WITHOUT DUCTS

In order to provide a comparison between ducted and unducted propellers in the light of a practical application, the transition and forward flight characteristics of an existing VTOL test bed were estimated.

The aircraft chosen is the DOAK 16 VTOL tilt duct machine and the calculation is for an unaccelerated transition at constant wing lift coefficient. The momentum methods outlined in References A1 and A2 were used under the assumption that the flow at the duct exit is parallel to the propeller axis. The results may be seen in Figure A1. Shown also is the variation of power required obtained from flight test measurements with the actual aircraft under nearly equilibrium conditions. These data were obtained through personal communication with TRECOM.

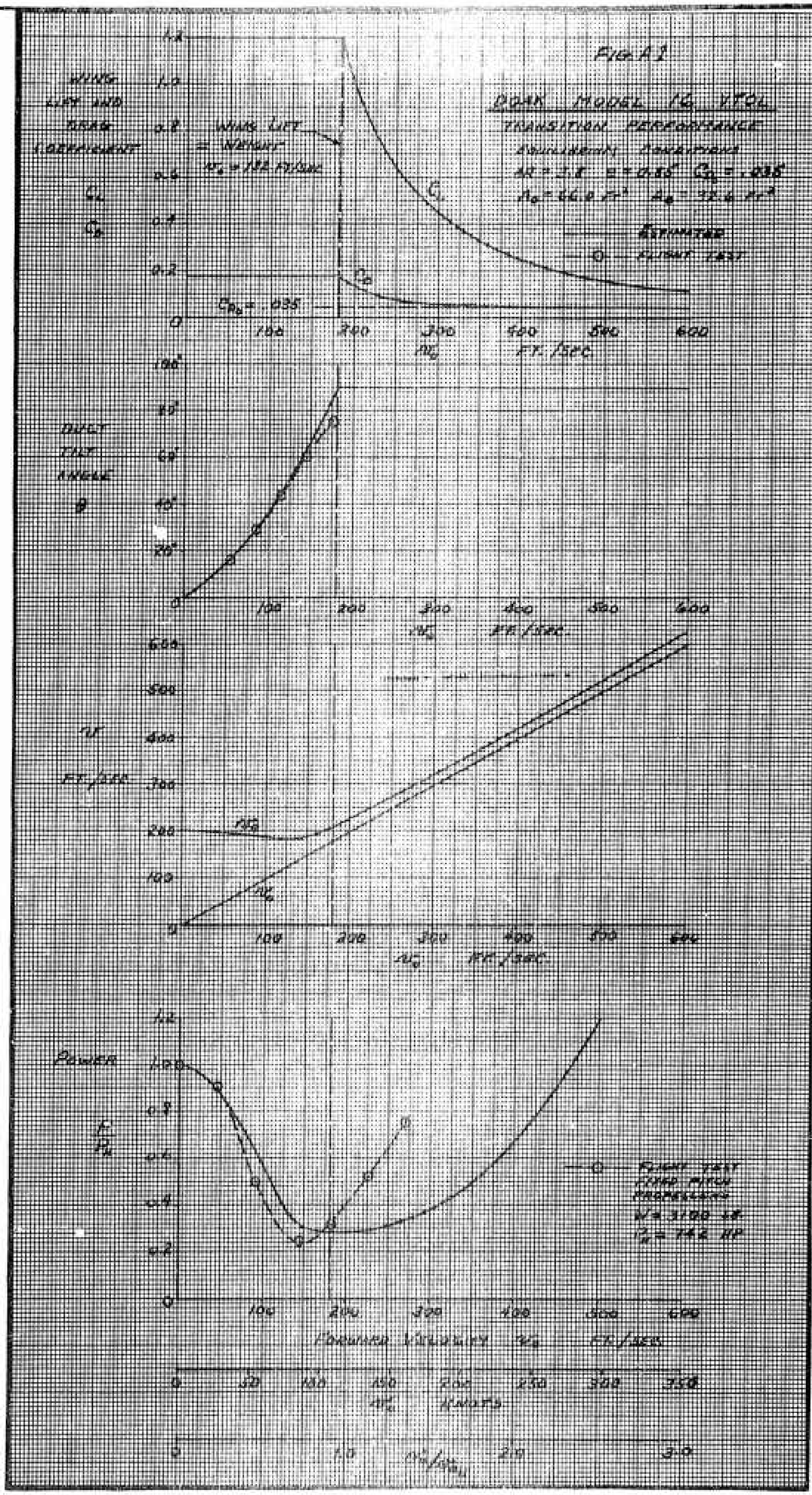
The correlation during transition is seen to be good, however, in forward flight actual power required exceeds the theoretical value by an appreciable amount. The reason for this, of course, is the fact that fixed pitch propellers are used in the actual machine whose efficiencies necessarily decrease as the forward speed increases.

Estimates of power required in forward flight for two hypothetical cases employing unshrouded propellers were made. The propeller diameter of these configurations were chosen so that the machine could be hovered with the same power as with the shrouded propeller (Figure A2). The propeller data used were those of Reference A3. It must be emphasized that the free propeller chosen for the comparison has low static efficiency. It was taken from the tests of R. M. Grose, the data of which were readily available. The low static efficiency is caused by the square tips of this propeller which are used primarily to obtain high power loading at supersonic tip speeds but are detrimental at lower speeds. In addition the Reynolds number of these tests is rather low which also contributes to the low efficiency.

It was then assumed that the propellers operated at (a) constant speed and variable pitch, and (b) constant pitch and variable speed. The results are shown in Figure A3. The ideal curve normalized to theoretical hovering power is reproduced from Figure A1. The other curves show that the variable pitch propellers as expected use much less power than the ducted fans and that the fixed pitch propellers use more than the variable pitch propellers. It should be noted, however, that this hypothetical case involves a propeller of 7.36 foot diameter. This particular 7.36 foot diameter propeller thus shows an improvement in this limited range. The experimental data used extended only to tip Mach numbers of about 1.1. Above 160 knots tip Mach numbers exceed 1.1. No experimental data were available for higher Mach numbers and power data shown may be too low since no devaluation of performance with Mach number was applied.

It is certain that a reduction in tip Mach number in forward flight and consequently improvements in efficiency could be made by increasing solidity either by adding another blade or by increasing blade chord. In this way the fixed pitch propeller would provide the same thrust at a lower tip speed and thus avoid the adverse effects of compressibility to some extent. The choice of a free propeller of this size may be undesirable for other reasons.

It is realized that the influence of structural and power plant requirements should be taken into account in order to make the comparison complete. Flow asymmetries during transition must also be considered. Obviously, the duct does direct the flow to some extent and it is taken for granted that flow asymmetries will be worse for a free propeller than with a propeller in a well designed duct.



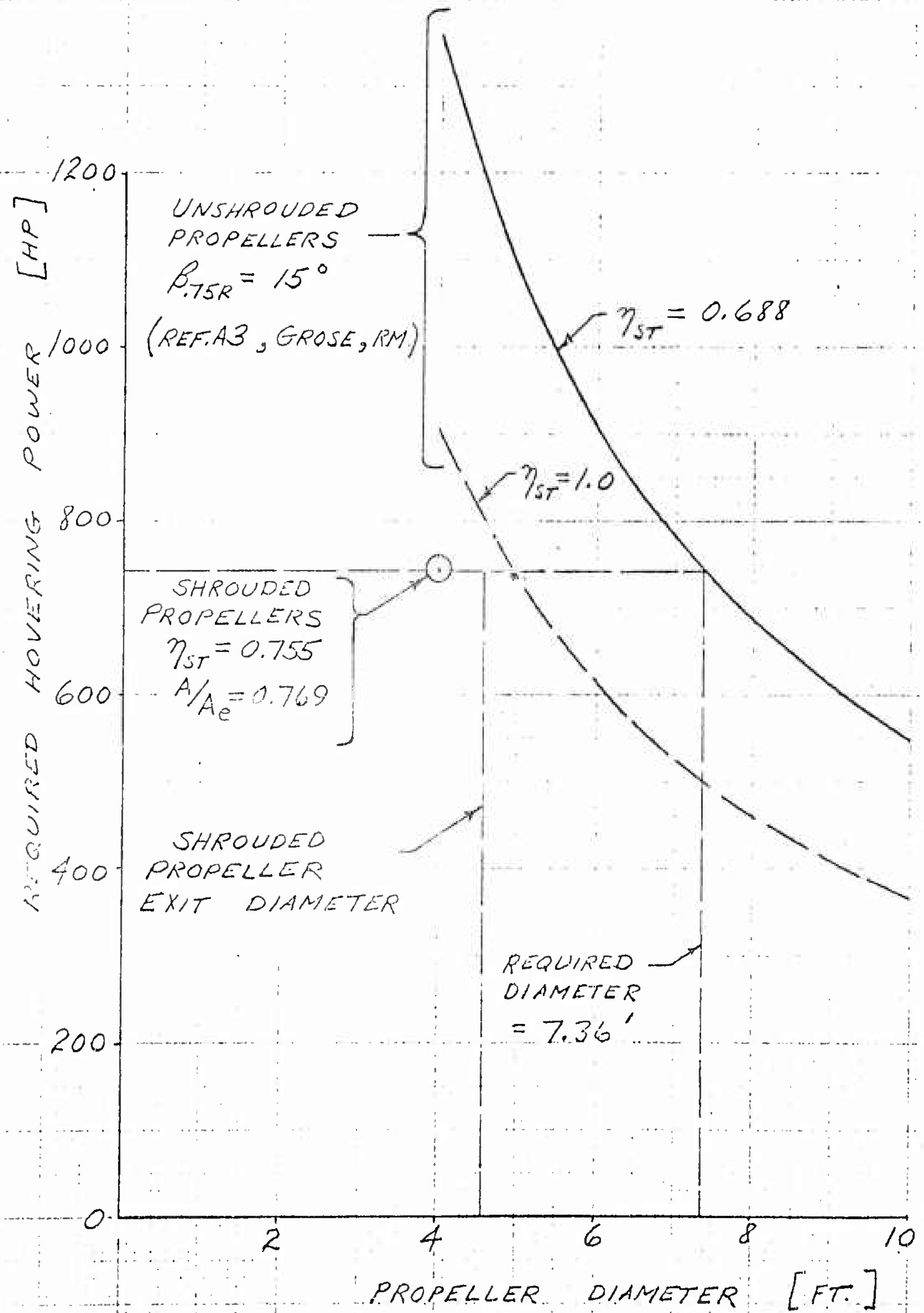
DOAK MODEL 16 VTOL
TRANSITION PERFORMANCE
EQUILIBRIUM CONDITIONS
ESTIMATED
FLIGHT TEST
WING LIFT AND DRAG COEFFICIENT
WING LIFT = WEIGHT
DUCT TILT ANGLE
FT./SEC.
POWER
FLIGHT TEST FIXED PITCH PROPELLERS
FORWARD VELOCITY
KNOTS

FIG A2

DOAK 16 VTOL

REQUIRED HOVERING POWER ~ STANDARD CONDITIONS

WEIGHT = 3100 LB.



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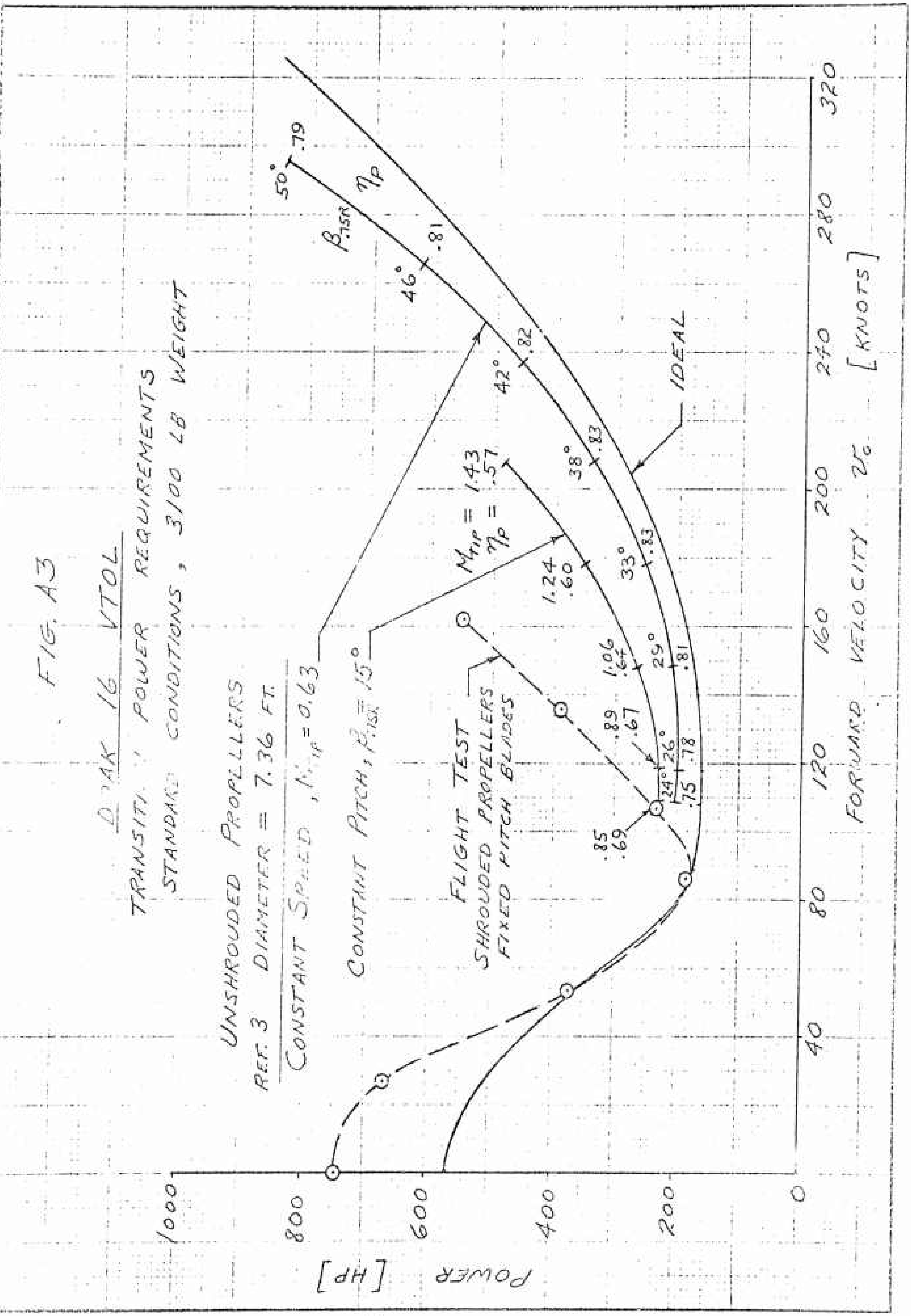


SECTION B

COMPARISON OF DUCTED AND UNDUCTED PROPELLERS IN HOVERING

The performance of a ducted and an unducted propeller as applied to a specific configuration, the DOAK 16 VTOL research aircraft, has been analyzed and the results are shown in the following.

Both propellers were designed for maximum efficiency in hovering. The data used in the ducted propeller analysis was obtained from flight test and wind tunnel measurements of the DOAK 16 performance while the free propeller performance was obtained from theoretical considerations outlined in references (B3) and B5) together with two-dimensional airfoil characteristics given in references (B1) and (B2). Propeller geometry may be seen in figure B1. The analysis is made for constant rotational speed and variable pitch and the results may be summarized by a plot of thrust and efficiency versus advance ratio v_0/nd. These plots may be seen for each propeller in figures (B7) and (B8). In order to make the results more descriptive, an unconventional efficiency was used which is explained in the following.

A propeller, in moving through a stationary fluid system at velocity v_0 while exerting a thrust T, does useful work and increases the kinetic energy of the fluid. Since, in normal forward flight, we are interested in obtaining useful work, the kinetic energy increase is in the nature of an induced loss since it serves no useful purpose. However, at static conditions, the forward motion is zero and the normally defined useful work is zero making the efficiency based on this quantity meaningless. The induced loss in this case is the desired quantity and efficiency should express how effectively power is converted into thrust. Therefore, a meaningful efficiency should, for static conditions relate the actual power required to produce a certain thrust to an ideal value required. In order to describe more fully the degree of perfection of a propeller which must operate down to zero forward velocity, we prefer to define an efficiency which uses as the useful output, the sum of the kinetic energy increase and the work done per unit time on the aircraft.

$$\eta = \frac{\text{useful work done/unit time} + \text{kinetic energy increase}}{\text{input shaft power}}$$

This formula describes the degree of perfection of a propeller at both static and forward flight conditions by providing a measure of the losses due to skin friction and imperfect loading. This "efficiency" is unity for a frictionless propeller with optimum load distribution. If $\dot{m}$ is the mass flow per unit time, the "efficiency" may be written as

$$\eta = \frac{T v_0 + \frac{\dot{m}}{2}(v_e - v_0)^2}{P} = \frac{T}{P}\left(\frac{v_e + v_0}{2}\right)$$

where v_e is the average axial component of wake velocity. At static conditions, the efficiency as defined is exactly equal to the commonly used "Figure of Merit" while in forward flight, it is unity for a frictionless propeller with perfect loading and approaches the propulsive efficiency $\frac{T v_0}{P}$ as the loading approaches zero. Such an efficiency will serve a useful purpose by defining the "efficiency" of a propeller designed for VTOL applications.

STATIC CONDITIONS

- For static conditions, the diameter of the free propeller must be $\sqrt{2}$ times the exit diameter of the ducted propeller in order to obtain the same ratio of thrust to power if the efficiencies are exactly equal. The free propeller considered in the following shows a higher efficiency than that for the ducted propeller and the required propeller diameter is 1.25 times the ducted propeller exit diameter. Chosen or given blade design papameters are given for both propellers in figures(B2)and(B3). The ducted propeller was designed by the methods outlined by D. Küchemann and J. Weber. These methods determine the velocity field in the shroud by the superposition of singularities representing the shroud and the propeller. The method outlined by Glauert was used to design the propeller to operate in this velocity field. The measured static efficiency is seen to be good for a ducted propeller (76%, fig. B6). Because of the shroud diffusion behind the propeller, the shroud appears to carry actually about half the total thrust. Propeller skin friction losses are estimated to be about 10% and the duct, centerbody and vane friction loss to under 3%. Exit stators are used to extract the rotation of the slipstream and inlet guide vanes are employed for control purposes.

The free propeller used for comparison was designed for static conditions by the methods given by Theodorsen, Lock and Goldstein in references (B3) and (B5).

The design criteria followed was to obtain ideal disk loading at zero forward speed. Estimated efficiency from strip theory using measured two-dimensional airfoil data shows about 86% . Another estimate of efficiency for this free propeller indicates skin friction losses of 9% and ideal rotational losses of about 4%, making the efficiency 87% . Skin friction losses were calculated by the equation

$$\frac{\Delta P}{P} = \frac{\pi^4}{4} \frac{C_F \, x^3 \sigma}{K_P}$$

where C_F is the skin friction coefficient for the Reynolds number at blade station x , usually taken at x = 0.75 and σ is the solidity at that station. The ideal rotational loss was obtained from Goldstein's solution of the rigid helicoidal vortex sheet model of the propeller given in reference (B3).

FOREARD FLIGHT (axial flow)

The forward flight performance of both propellers may be seen by examination of figures B5, B6 and B7. The dotted curves are the required thrust coefficients for level flight. It is seen that for a variable pitch propeller, tested at the Ames wind tunnel, the "efficiency" decreased with increasing forward speed to values in the order of 20-30%. It appears that this ducted propeller is not designed to operate efficiently at low thrust coefficient in forward flight. The low efficiencies at small thrust are caused by non-uniform blade loadings in which the tip sections thrust and the root sections drag. In addition, compressibility effects at the tip tend to deteriorate the remaining tip performance. Duct drag is small compared to total thrust required for level flight.

The free propeller apparently does not suffer as much in forward flight. Inspection of figure B7 shows maximum efficiency of 70% in level flight occurs at a speed of 220 knots. Blade loadings at these speeds are non-uniform, however, the root sections drag only slightly. The tip sections are subjected to slight compressibility while the intermediate sections operate efficiently.

The required power for the DOAK 16 in level flight is shown in fig. B8 for each propeller configuration assuming variable pitch. The advantage of the free propeller may be seen. The actual DOAK 16 with ducted fixed pitch propellers consumes less power than that indicated by the variable pitch curve because efficiency is increased slightly due to increased rotational speed.

The performance of each is summarized below:

	Shrouded Propeller	Free Propeller
Design point	static conditions	static conditions
Propeller diameter	4.0 ft.	5.7 ft.
Final jet diameter	4.57 ft.	4.03 ft. (static)
Jet velocity (static)	260 ft/sec	250 ft/sec
Design thrust	1,550 lb	1,550 lb
Design power	371 hp	371 hp
Rotational speed	4,800 rpm	3,000 rpm
Tip mach number (hovering)	0.90	0.77

	Shrouded Propeller	Free Propeller
Static Conditions		
Efficiency	.76	.86
$\beta_{.75R}$	25°	15.75°
Thrust	1,550 lb	1,550 lb
Rotational loss	------	4°/o
Skin friction loss	10°/o propeller, 3°/o duct, centerbody, stators and vanes	9°/o
Forward flight		
Efficiency	.20 - .30	.60 - .70
$\beta_{.75R}$	35°	35°
Thrust	250 lb	250 lb
Duct drag coefficient (based on duct projected side area)	.007	-----
Maximum speed (for 800 hp)	164 knots	277 knots

CONCLUSIONS

1. For the propellers examined, it was found that the free propeller which was designed to match the hovering performance of the ducted propeller (identical thrust and power) by an appropriate increase in the diameter, experienced a 16°/o loss in efficiency in forward flight compared to 46°/o lost by the ducted propeller. It is restated that these results are for variable pitch and constant rotational speed.

2. It appears that the reduction in performance in forward flight of the shrouded propeller is due to the static non-uniform axial velocity distribution characterized by an excess velocity near the shroud surface at zero or low forward velocity. This effect does not occur in the free propeller which is designed statically for a uniform inflow velocity distribution. A propeller designed for static conditions has an excess twist which causes tip and root losses in normal flight. The ducted propeller represents the most adverse case.

3. For the constant pitch propeller, the ducted propeller appears slightly more favorable since the range of advance ratio is smaller than that of the free propeller.

4. Engineering compromise requires a reduction in duct diameter with a slightly larger than normal tip speed which effect is adverse.

LIST OF SYMBOLS

A	Propeller disk area	$\frac{\pi d^2}{4}$
A_e	Shroud exit area	$\frac{\pi d_e^2}{4}$
B	Number of blades	
β	Blade Pitch angle	
c	Blade chord	
C_F	Skin friction coefficient	$\frac{F}{\frac{\rho}{2} v^2 S}$
C_L	Blade lift coefficient	$\frac{dL}{\frac{\rho}{2} W^2 c\, dr}$
d	Propeller diameter	
d_e	Shroud exit diameter	
F	Skin friction	
h	Blade thickness	
J	Advance ratio v_o/nd	
K_T	Thrust coefficient	$\frac{T}{\rho n^2 d^4}$
K_P	Power coefficient	$\frac{P}{\rho n^3 d^5}$
ℓ	Duct length	
$\dot{m}$	Mass flow per unit time	
M	Mach number	
n	Rotational speed rev./sec.	
η	Total "efficiency"	$\frac{T}{P}\left(\frac{v_o + v_e}{2}\right)$
η_P	Propulsive efficiency	$\frac{T v_o}{P} = \frac{K_T}{K_P} J$
η_{ST}	Static efficiency	$\frac{T}{2P}\sqrt{\frac{T}{\rho A}}\sqrt{\frac{A}{A_e}} = \frac{1}{\sqrt{\pi}} \frac{K_T^{3/2}}{K_P} \sqrt{\frac{A}{A_e}}$
N	Rotational speed RPM	

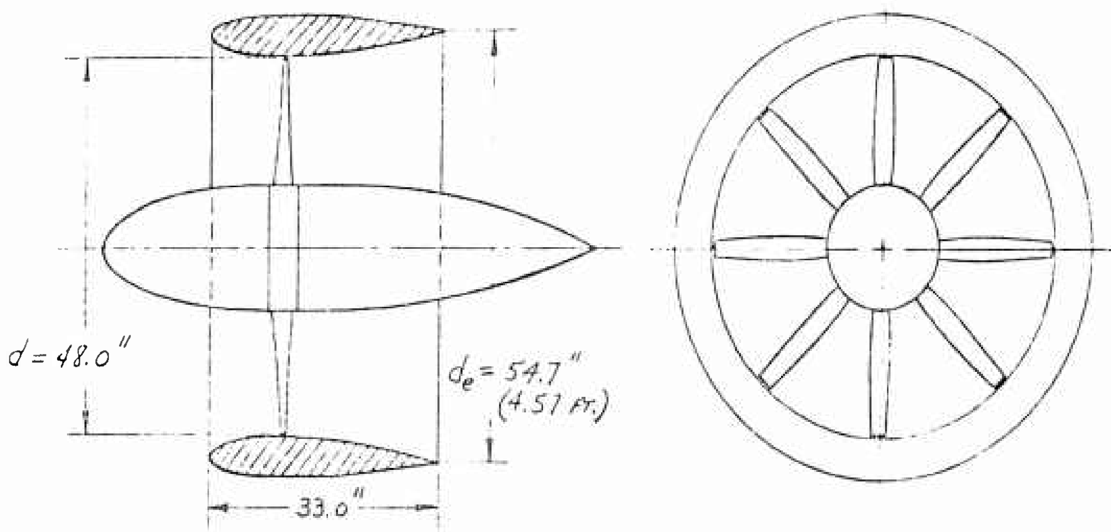
LIST OF SYMBOLS (Cont'd.)

ρ	Density of air
P	Power
r	Blade station radius
R	Propeller radius
S	Wetted area
T	Thrust
v	Local velocity
v_i	Axial inflow velocity in propeller plane
v_e	Jet velocity
v_o	Free stream velocity
W	Blade section relative velocity
x	Blade station radius r/R
σ	Blade solidity $\frac{Bc}{2\pi r}$
L	Blade section lift

FIG. B1

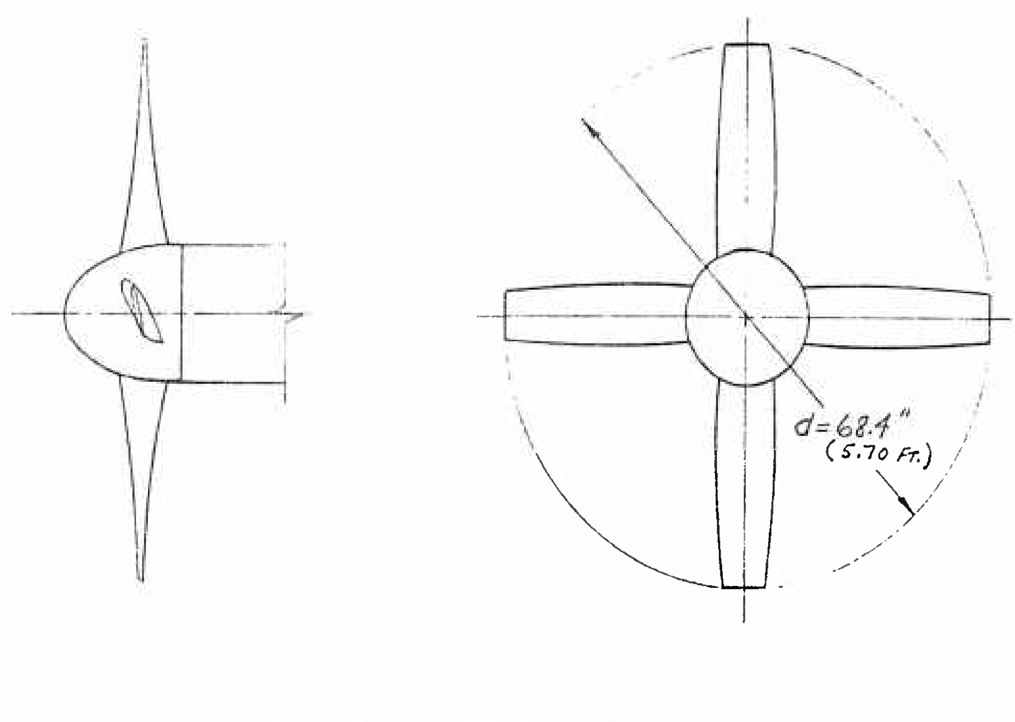
GEOMETRY

SCALE : 1 MM. = 1 INCH



SHROUDED PROPELLER (DOAK 16)

INLET GUIDE VANES AND EXIT STATORS NOT SHOWN



UNSHROUDED PROPELLER

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FIG. B2

DOAK 16 VTOL

DUCTED FAN PROPELLER GEOMETRY

DESIGN POINT ~ STATIC CONDITIONS

d - 4.0 FT. $\beta_{.75R}$ = 25° 8 BLADES

M_{TIP} = 0.9

K_T = .402 K_P = .169

η_{ST} = 0.76

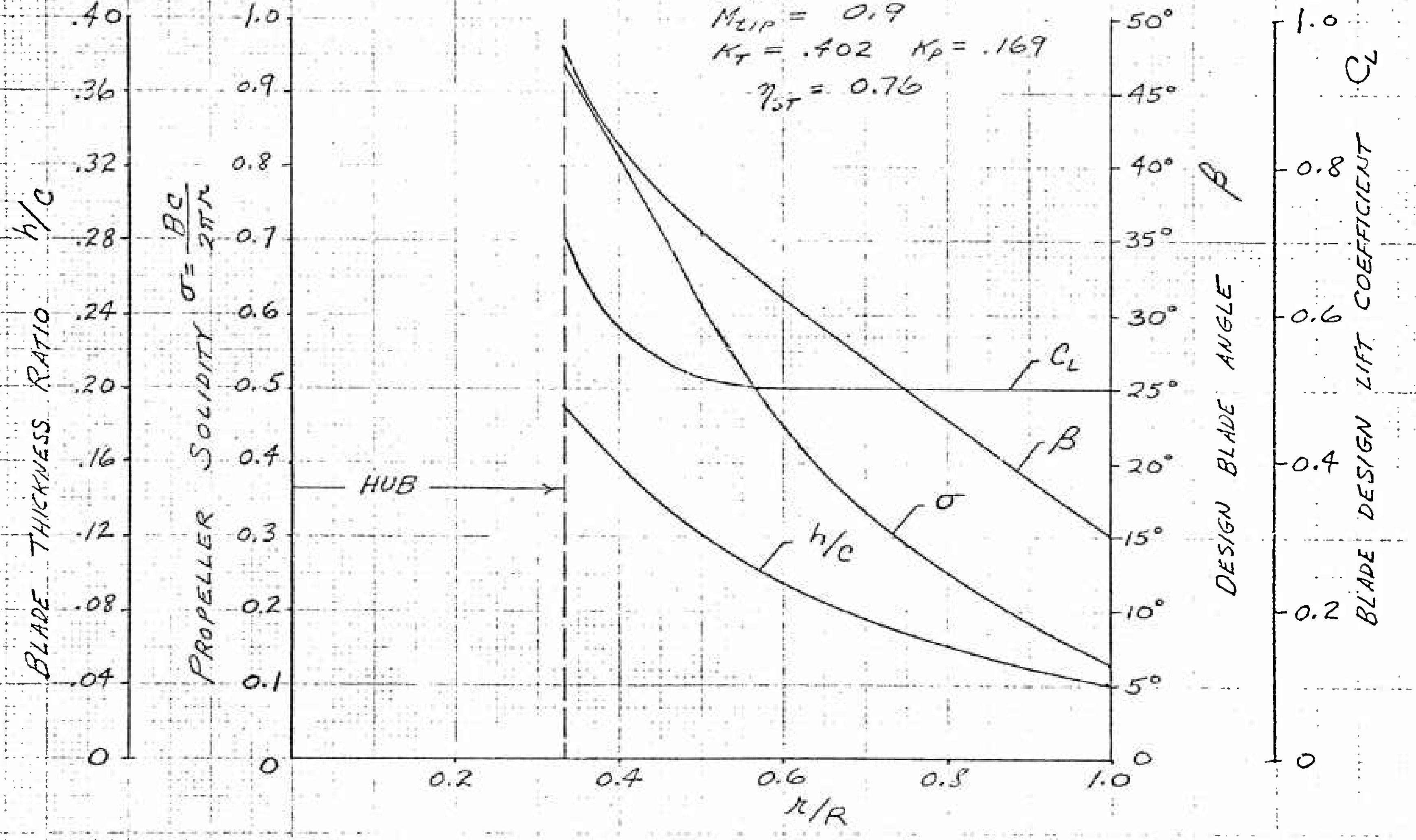

FIG. 23
STATIC UNSHROUDED PROPELLER

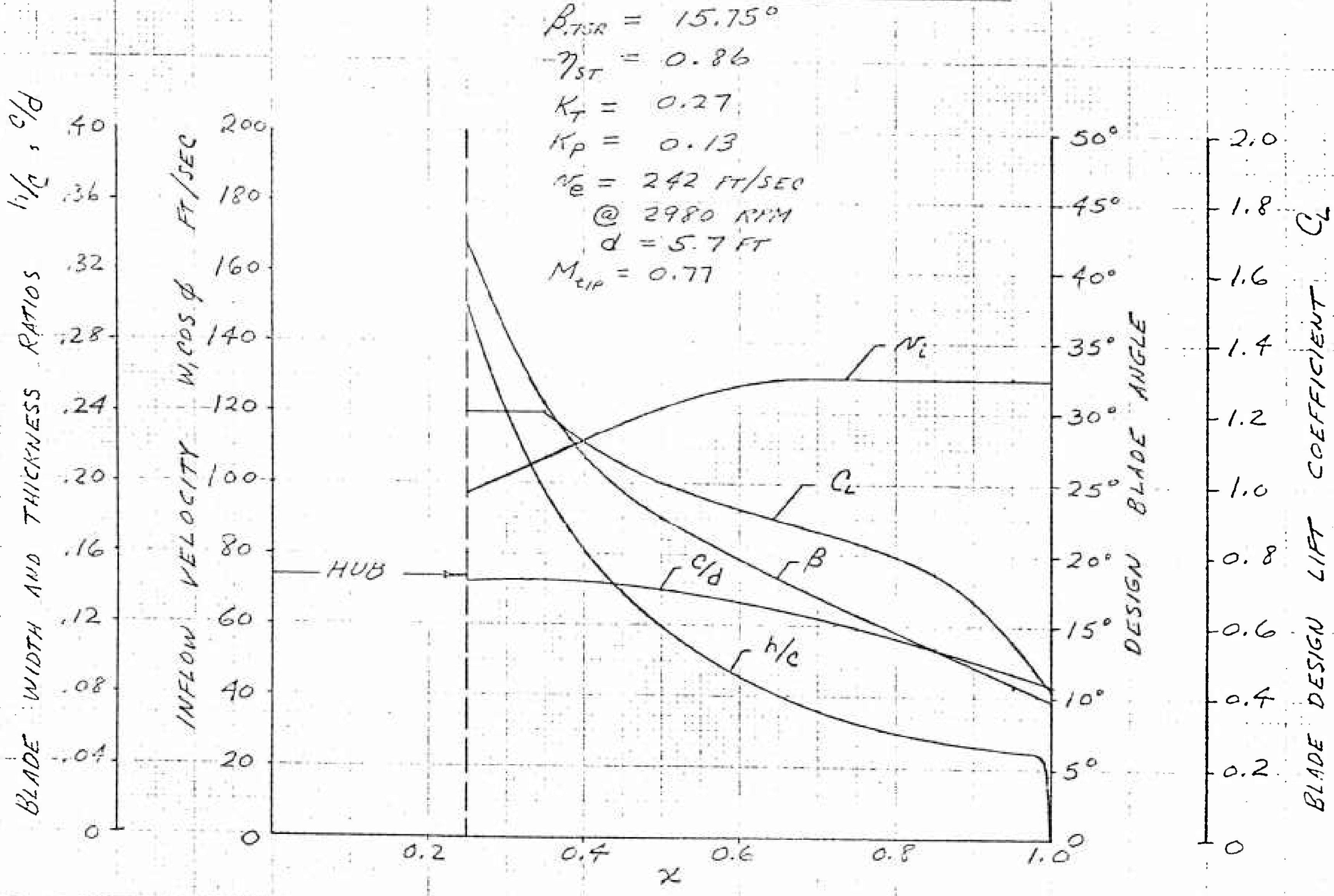

FIG. B4

STATIC UNSHROUDED PROPELLER

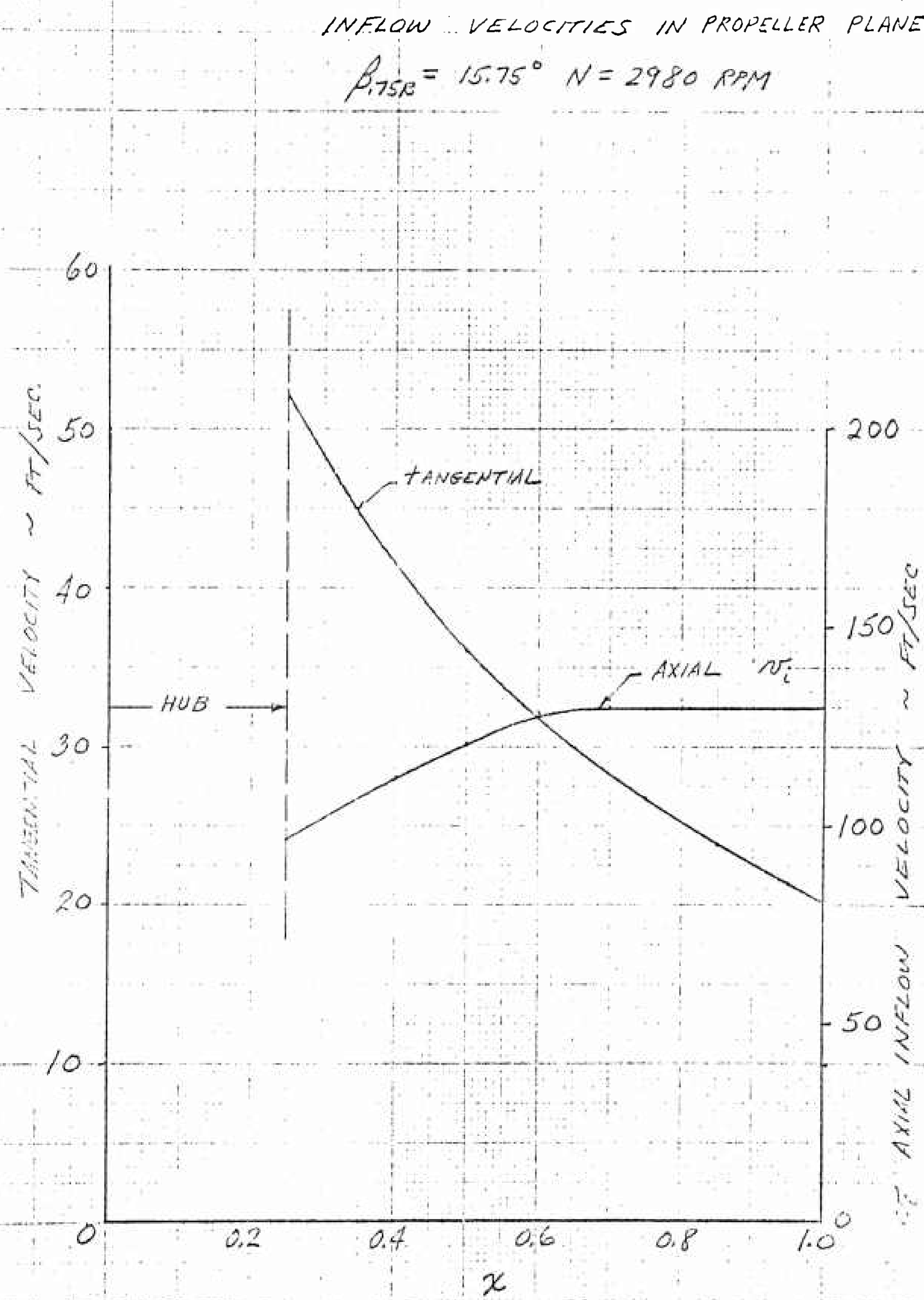

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FIG. B5

DOAK 16 VTOL

DUCTED PROPELLER PERFORMANCE IN AXIAL FLOW

$d = 4.0$ FT $\quad \frac{A_e}{A} = 1.3$

MEASURED DATA FROM AMES FULL SCALE TEST

$$\eta_p = \frac{T v_0}{P} = \frac{K_T}{K_P} J$$

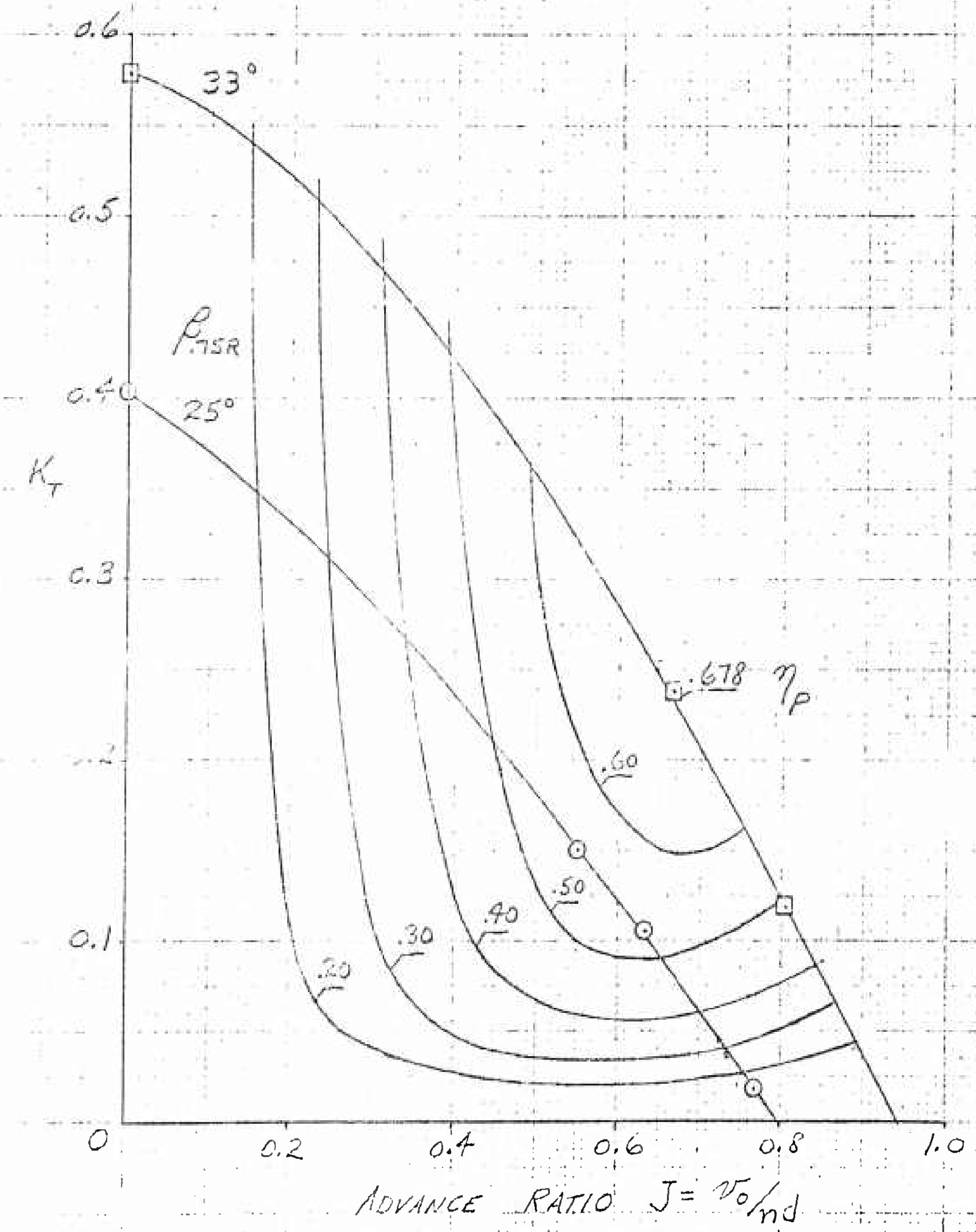


FIG. B6

DOAK 16 VTOL

ESTIMATED* DUCTED PROPELLER "EFFICIENCY" ~ AXIAL FLOW

$d = 4.0$ FT $\quad \frac{A_e}{A} = 1.3$

$$\eta = \frac{T}{2P}(v_o + v_e)$$

* ESTIMATED FROM AMES FULL SCALE TEST DATA

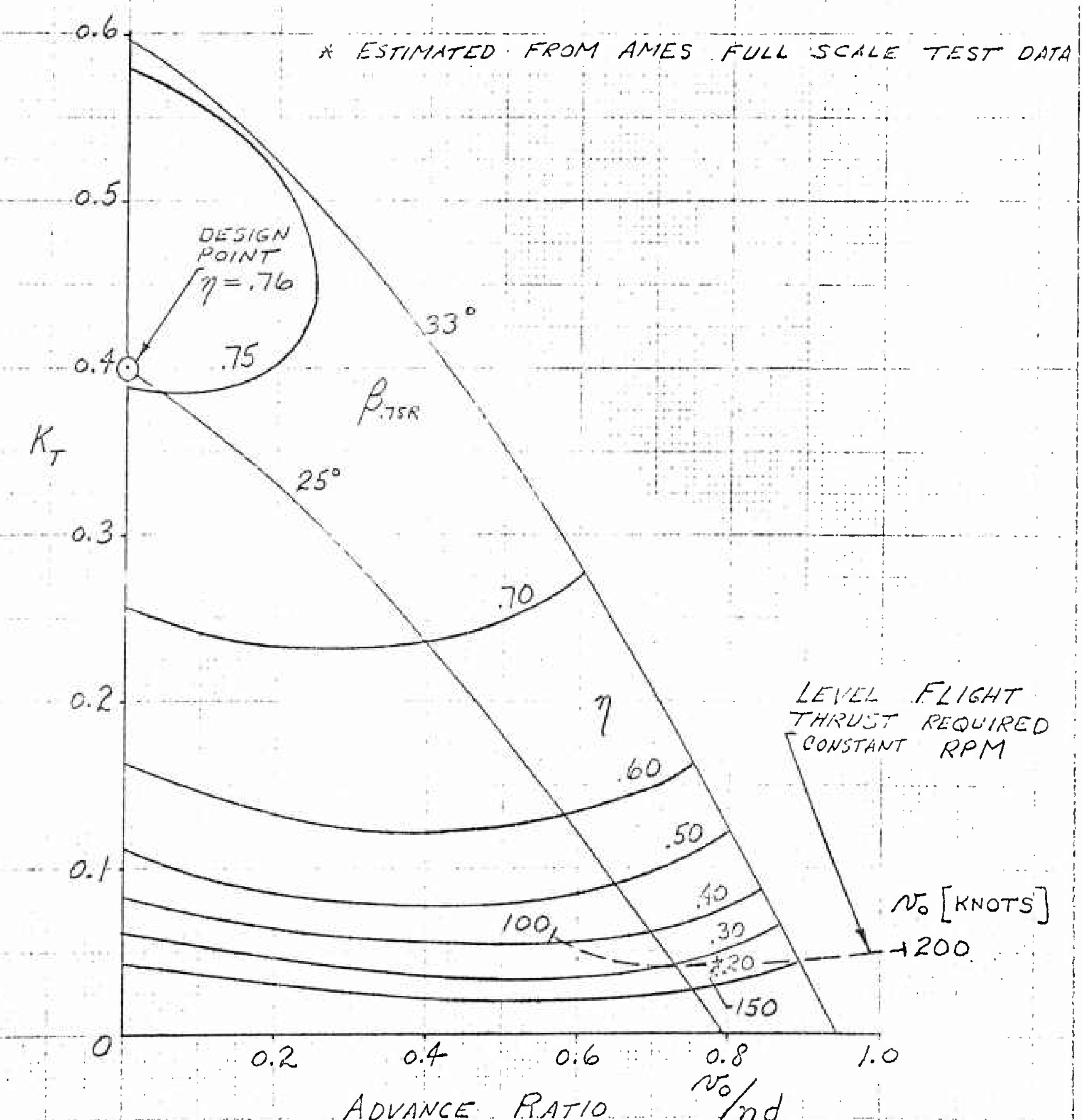


FIG. B7

STATIC UNSHROUDED PROPELLER
"EFFICIENCY" IN AXIAL FLOW
$d = 5.7$ FT $M_{TIP}(v_0/nd = 0) = 0.77$

$$\eta = \frac{T}{P}\left(\frac{v_0 + v_e}{2}\right)$$

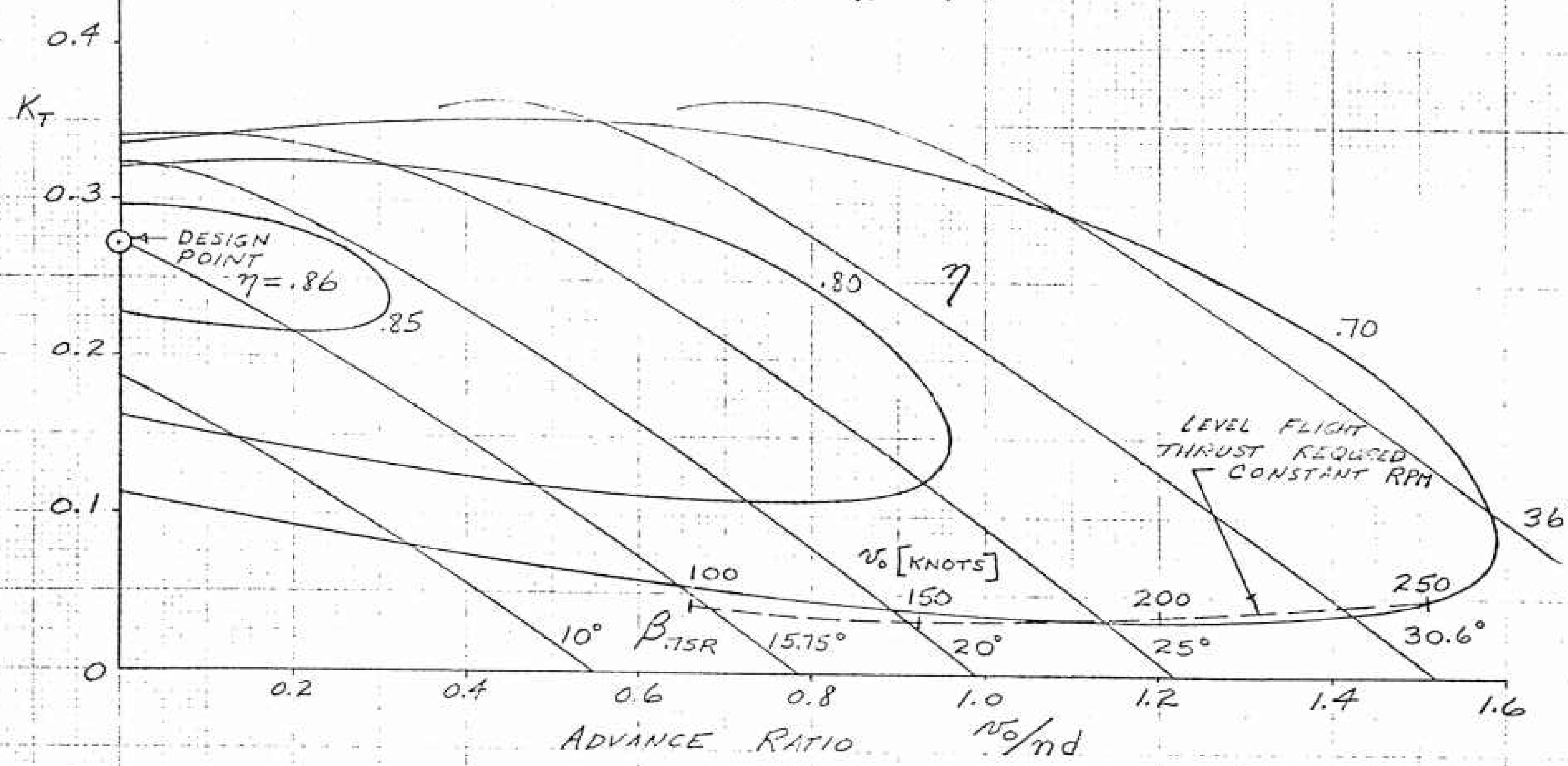
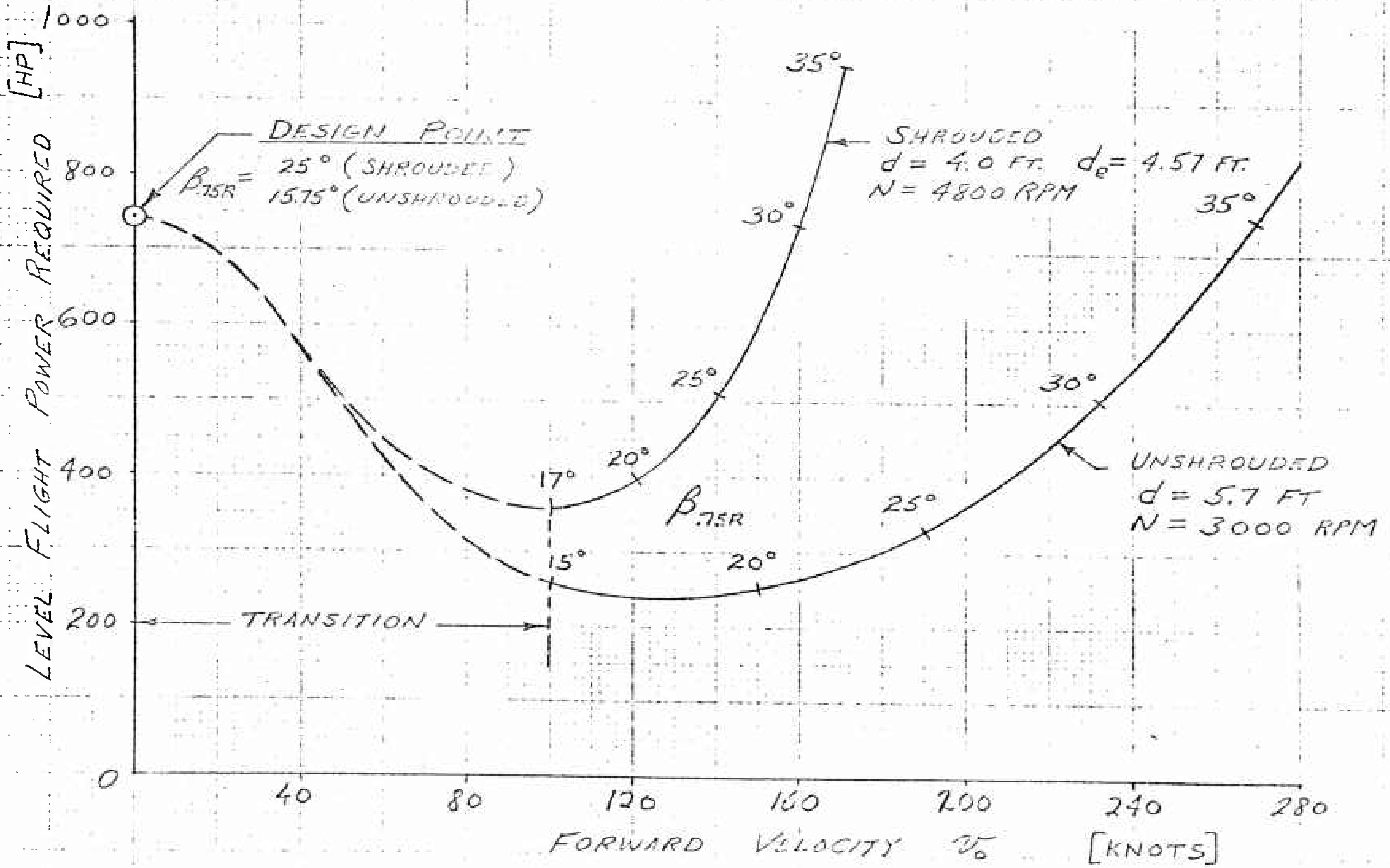


FIG. B8

A COMPARISON OF SHROUDED AND UNSHROUDED PROPELLER PERFORMANCE AS APPLIED TO THE DOAK 16 VTOL AIRCRAFT, WEIGHT = 3100 LB.



SECTION C

TABLE OF CONTENTS

ACCORDING TO AIRCRAFT TYPE

SECTION C

REVIEW AND COMMENTS ON THE DEVELOPMENT OF THE VTOL AIRCRAFT

ABSTRACT

This paper represents a brief review of the development of VTOL aircraft. An attempt is made to attain a broad perspective of the present status of VTOL development, to analyze specific problems encountered in the development and to indicate future research aspects.

A. INTRODUCTION

It might be well suitable to ask why one would desire the vertical take-off c[illegible]raft and why this particular aspect has cent[illegible] more and more int[illegible]t and activity on itself.

[illegible] first reason is [illegible]iously that a vertical take-off capability [illegible]pears very convenient. [illegible] would avoid the need for large prepared and c[illegible]ly airfields. This would tremendously increase the usability of the aircraft in any kind of military deployment as well as cut down travel times for civilian aircraft use. The reduction in travel time becomes relatively more important the shorter the total trip time becomes either through medium to short distance employment of the aircraft, or through increase in aircraft speed. Another reason why increased effort has been extended to the vertical take-off airplane is that the technical development made it look practically feasible. Comparatively large installed power is needed in modern supersonic aircraft and the step to full vertical take-off capability appeared smaller than at any time previously. Concurrent developments in aircraft engines also have brought about engines with less and less weight per pound of thrust, and indeed engines delivering five to eight pounds of thrust for every pound of their own weight are available today.

While the last two reasons may have played an important role in getting the VTOL effort started, it turned out that great difficulties obstructed an early realization of the concept of the VTOL aircraft. It became evident that technical refinements and tedious development work were necessary. It is the object of this report to review this development work and discuss various alleys of attack that have been pursued up to the present.

B.I. GENERAL REMARKS

In the development of VTOL aircraft, three phases can be distinguished. The first phase is characterized by more or less scattered attempts to realize VTOL capability in an aircraft and extends in time from the early 40's to the early 50's.

The second phase is characterized by a more systematic approach in which various possibilities are explored and usually a prototype is built by one or more groups or companies with the aim to demonstrate feasibility and, if possible, practical usefulness. This second phase extends from the early 50's to approximately the present time or possibly a few years hence. The work done during this phase will constitute the major part of this report and we will try to show the various solutions and, if possible, give an evaluation of their respective merits.

The third phase which we believe is about to start now, will consist of reducing to practice, one or more of the approaches investigated during the second phase with the aim to produce in larger numbers, aircraft suitable for certain specific tasks or applications and possibly to produce aircraft which extend and combine the VTOL capability with truly high speed flight performance.

In dealing with the aircraft produced and investigated during phase two, we will divide them into two classes. In the first class we will list and treat aircraft in the true sense of the word, meaning machines having some resemblance to conventional aircraft insofar as they go through a transition from hovering to forward flight and attain finally nearly conventional aerodynamic operation. In the second group, we will briefly deal with what is commonly known as air cycles, flying platforms, or aerial jeeps, i.e., machines of more or less unconventional design, developed for a specific purpose and usually having limited pay load and range capability; aerodynamic flight, i.e., flight based on wing lift is not attempted nor achieved.

B.II. VTOL AIRCRAFT

Table CI is a representative list of the aircraft developed in the second phase, i.e., designed and developed as experimental prototypes during the last decade. All the listed machines have been built and those marked with "F" have also been flown and have made successful or acceptable transition from hovering to forward flight.

The aircraft are arranged approximately in order of increasing area loading. Area loading is the quotient of aircraft gross weight over the total area of the lifting device, e.g., the rotor or propeller disc.area. Arrangement in order of increasing area loading makes it possible to divide the various aircraft quite naturally into groups. These groups as shown in the first column in the table are:

(a) the unloaded rotor aircraft

(b) the tilted rotor aircraft

(c) the deflected propeller slipstream aircraft, and the tilted rotor-propeller and wing aircraft

(d) the submerged ducted fan aircraft

(e) the tailsitter propeller aircraft

(f) the tilted ducted fan aircraft

(g) the jet aircraft subdivided into tilted jet deflected jet, submerged jet, tailsitter jet, and tailsitter jet coleopter

The next column in Table CI shows values of the area loading in pounds of gross weight per square foot of effective area. The third column shows the values of the power loading for the respective aircraft, i.e., the numerical value that indicates how many pounds of gross weight are carried per installed horsepower. Naturally, this value decreases with increasing area loading. Given area loading and power loading for a specific aircraft the hovering efficiency can be determined. This value is shown in the next column. A major performance characteristic, the cruise flight speed of the aircraft, is shown in the next column. The downwash velocity of the aircraft in hovering which is proportional to the square root of the area loading is shown in the next column. This quantity gives an indication of the ingestion and erosion problems to be encountered in operating the particular aircraft. Values of the gross weight of the aircraft and the designation of the power plant form the last two columns of the table.

The various groups of VTOL aircraft and typical representatives within each group are discussed in the following.

B.II. a. UNLOADED ROTOR AIRCRAFT

The unloaded rotor type aircraft are the closest relatives to the helicopter. They are characterized by a comparatively large rotor which is loaded nearly as low as in a helicopter, and which is used for the VTOL operation. In addition, they have a conventional wing and propulsive means, usually propellers. The transition to forward flight is effected by increasing the power directed to the propellers and finally disengaging the rotor or reducing to zero the power fed to the rotor leaving the rotor autorotating and carrying only a fraction (in the order of 30%) of the weight. By the unloading of the rotor, the detrimental effect of the stall of the retreating blade is reduced and the speed is correspondingly increased from ~ 100 knots obtainable with the helicopter to ~ 170 knots.

A representative of this kind of airplane is the McDonnell XV-1 which represents at the same time, one of the earliest VTOL efforts in the United States. Another example is the much larger aircraft developed in Great Britain and reportedly in commercial operation. In both these airplanes the rotor is driven by tip-jets, i.e., the reaction of high pressure air-jets discharged tangentially at the tip of the rotor blade. In the latter case, the jet momentum is increased by injecting and burning fuel just before discharge. This method of driving the rotor is quite attractive for aircraft of this kind because it saves the complication and weight of a mechanical train and because its disadvantage, less efficiency and therefore higher fuel consumption, is relatively less important in an arrangement that uses the rotor only for very short periods.

B.II. b. TILTING ROTOR AIRCRAFT

The tilting rotor type aircraft listed in the next group are one step further removed from the helicopter insofar as the configuration is changed by tilting the rotors forward in the process of transition and they are then used like conventional propellers in forward flight. This method requires higher area loading on the rotors because a compromise must be made between their operation as lifting rotors and as propellers. To improve the compromise, it is desirable to change the gear ratio between engine and rotor. Nevertheless, the propeller operation is inefficient since the propeller is necessarily much too large and the blades have inadequate twist for high speed flight. This limits the maximum flight speeds attainable to the speeds obtainable with the unloaded rotor type aircraft.

The most outstanding representative of this class of aircraft is the Bell XV-3 which employs two rotors at the tips of the wing. The aircraft has undergone some modifications following some mishaps in flight testing and is at present still under development. It has, however, made quite successful flights. Transition is accomplished easily and smoothly and may be stopped at any point. Forward flight propulsive efficiency exceeding 0.8, obtained with high gear ratio, was achieved only for speeds of up to 120 knots.

B.II. c. DEFLECTED PROPELLER SLIPSTREAM AND TILT WING AIRCRAFT

In the next group are collected the deflected propeller slipstream and the tilt-wing aircraft. This is a group using nearly conventional propellers with correspondingly higher area loading.

The deflected propeller stream type aircraft are characterized by conventional arrangements of wing and propeller, i.e., the angle of the propeller axis with respect to the fuselage is fixed. To obtain vertical take-off, the propeller slipstream is turned approximately 90° downward by flap or cascade arrangements. In transition, the flaps are gradually retracted or straightened out, reducing the angle of deflection of the propeller stream until finally a conventional aircraft configuration is obtained.

A representative of this class of aircraft is the Ryan Vertiplane which has been tested extensively by the manufacturer and NASA. A great deal has been learned from this experimental airplane about the control problems and it appears that successful airplanes of this type could be built with the knowledge acquired.

In the tilt-wing aircraft, the relative position between propeller axes and wing is fixed and the total assembly is tilted with respect to the fuselage of the aircraft. For vertical take-off, the assembly is tilted to a position where the propeller axes point vertically upward. After lift-off, the angle between propeller axes and fuselage is gradually reduced until a conventional airplane arrangement is obtained at the end of transition to forward flight.

A representative example of this kind of aircraft is the Vertol 76. This airplane has been thoroughly tested by the manufacturer and NASA and has made many successful flights. The maximum flight speed is not much larger than the speeds obtainable with conventional helicopters and less than those obtained in the preceding groups. The reason for this may be that no emphasis was placed on flight speed. Slow conversions were possible without large changes in trim stick position. Another example in this group is the KAMAN K-16 VTOL seaplane, also designed as an experimental aircraft. Performance data for this aircraft are not yet obtainable.

B.II. d. SUBMERGED FAN AIRCRAFT

Another solution to effect vertical take-off capability is the so-called submerged fan arrangement. As the name implies, one or more lifting fans or propellers are positioned in cutouts in the wing or fuselage, their axes vertical in the normal take-off or flight position. Since the space available for the fans is naturally limited and constitutes only a fraction of the area of the planform, it is evident that arrangements of this kind are of necessity higher up on the scale of area loading. The arrangement, nevertheless, has some attraction since it encloses the means for vertical take-off within the final forward flight shape and, therefore, makes it possible to design this final shape properly for high speed flight. The submerged fan solution has received further stimulation by the fact that an engine manufacturer has proposed and developed a complete propulsion unit incorporating this principle, This unit consists of two main parts, a conventional jet engine and a lift fan. The lift fan is the inner part of a rotor whose outer part is a gas turbine. Rotor and jet engine are connected by ducting. The exhaust gases from the jet engine are directed to the top turbine of the rotor by a deflector valve and thus drive the vertical lift fan. In transition, the jet from the fan is first deflected rearward and finally the deflector valve is retracted which leaves the jet engine working as a conventional propulsion engine.

There is only one submerged fan airplane built at present. This airplane does not use the gas turbine system described above. However, a number of projects (see Section BV) are under development and it is to be expected that some of this type aircraft will be built and tested in the near future.

B.II. e. TAILSITTER PROPELLER AIRCRAFT

Another approach to vertical take-off is incorporated in the so-called tailsitter airplane. Instead of providing means for changing the direction between thrust and airplane axes, these airplanes are designed to be landed and to take off in a nose-up position. The idea is simple enough and the feasibility has been proved. Nevertheless, the complications and inconveniences of landing the aircraft in a vertical position must have been felt to be severe enough so that no future work on this type of aircraft is going on or is being considered.

The two entries in this field are the Convair XFY-1 and the Lockheed XFV-1. Both these airplanes use the same powerplant-propeller unit which was developed specifically for this application. The Convair XFY-1 has made successful flights. The Lockheed project was terminated after only limited flight testing.

B.II. f. TILTED DUCTED FAN AIRCRAFT

In the next group, the tilted ducted fan aircraft, we find a single airplane, the DOAK 16. This airplane employs two rather highly loaded fans on each wing tip. The fans are enclosed in shrouds and the whole fan-shroud units can be tilted with respect to the airplane from a right angle position between fan axes and fuselage axes (vertical) to a nearly parallel position (horizontal). The airplane has made successful transition flights and has also demonstrated the ability to operate as a STOL airplane, i.e., the ability to take off on short runways with the propeller axes tilted only slightly upward.

B.II. g. JET THRUST AIRCRAFT

In the last group, we have combined all the VTOL airplanes using direct jet thrust as take-off and propulsion means. This group contains the airplanes with the highest area loading. In the tilted jet aircraft, an example of which is the Bell Air Test Vehicle, the whole jet engine is tilted with respect to the airplane and finally turned back to normal position after transition to forward flight. In the Bell X-14, the exhaust of two jet engines is deflected by a cascade arrangement for vertical take-off. A British aircraft of this type uses four small jet engines which are mounted with axes nearly vertical submerged inside the fuselage. These engines have limited tilt capability to adjust for the transition maneuver while a fifth engine is mounted in a horizontal position and supplies the propulsion force for forward flight. A tailsitter jet has been built by Ryan and has made successful flights. A French entry can be classed as a tailsitter jet with a ring-wing instead of a normal wing. Only limited flights with an engine test bed have been made in the coleopter program.

B.III. AERIAL PLATFORMS AND JEEPS

Aerial platforms and jeeps are listed in Table CII. This class is typified by the fact that no attempt to approach the airplane configuration in forward flight is made. The flying platform vehicles are the result of an early demonstration by NASA that a person could easily stand and maneuver slightly on a platform supported by a jet thrust. The attractiveness of such a machine as an airborne personnel carrier is evident. During the development of the Hiller platform and the DeLackner Aerocycle the "kinesthetic" type of control was proved to be feasible. However, aerodyanmic problems associated with the design of ducted fans and rotors limited the performance of these vehicles. In the case of the Hiller platform, high duct nose-up pitching moments occurred, requiring an excessive pilot weight shift to achieve even low speeds. High nose-down tilt also was required. These problems were not so pronounced with the open rotor aerocycle, however, fluctuating loads on the blades caused the performance with the rigid rotors to be not satisfactory.

The army has long desired to possess a compact vehicle having the versatility of the ground jeep but being capable of hovering and propelling itself above the ground. The aerial jeeps represented in Table CII are the result of the army's jeep development program. The vehicles demonstrated the ability to carry moderate loads over short distances at speeds of up to 40 knots. The complexity of the machines, however, approached that of helicopters in that semi-helicopter type controls were found to be necessary. In addition, automatic stabilization was found to be desirable as the machines had stick-fixed instabilities about all axes. It has been shown that vehicles of this type could be built but at the expense of high installed power and control system complexity.

B.IV. GRAPHICAL SUMMARY

A summary review of the VTOL airplane machines contained in Table CI and CII (plus some helicopters) is shown in Figure C1. This graph is obtained by plotting associated values of hovering downwash velocity and flight velocity for each airplane. The systematic arrangement of all the airplanes in this graph is more clearly seen in the following Figure C2 which was derived from the first plot by connecting airplanes in a group and occasionally extrapolating.

Starting near the origin of the plot is the group of helicopters; lying very nearly on a straight line and slightly above it are the loaded rotor type airplanes with moderately improved speed capability. Near the origin is also the flying platform and aerial jeep group representing a group of relatively low flight speed and high downwash velocities. Indeed this group is the only one that falls below the $\frac{v_o}{v_{e_H}} = 1$ -line represented in the graph by a 45° line through the origin. Following in order of increasing downwash velocity, are the propeller driven airplanes and slightly above and possibly extending to higher flight speeds, the ducted fan-in-wing aircraft. The propeller tailsitter airplanes fare quite well in that they attain fairly high flight velocities with still moderate downwash velocities. However, it must be remembered that these airplanes are intercepter type planes with hardly any payload or range. The jet airplanes are located high up on the scale of downwash velocities and are also the fastest airplanes realized at present.

B.V. DEVELOPMENT WORK IN PROGRESS

Sikorsky, Hiller and Vertol are investigating the stored rotor concept. Vertol, under sponsorship of the Army and Navy, is conducting a research study on a submerged fan machine which is called a Vertodyne. It has shaft-driven ducted fans submerged in the wing with provisions for covering the ducts in forward flight. The Ryan studies involve the use of a ducted fan driven by turbine blades on the periphery of the fan rather than by shafting as in the case of the Vertodyne. Wind tunnel tests of a full scale fuselage submerged fan aircraft are being conducted by NASA. A tilting propeller type of VTOL aircraft which features large diameter propellers designed to provide lift as well as propulsive forces, has recently been flown. The craft is reported to have flown at speeds up to 200 mph. It is designed as a light executive transport. A VTOL strike-reconnaissance aircraft is under development in England. It is ducted fan design utilizing a ducted fan engine with four nozzles, all of which can be swiveled to point down or to the rear. Two nozzles take the cold flow from the fans, the other two the hot flow from the exhaust. Normal, short and vertical take-off, therefore, are all possible.

C. CONCLUDING REMARKS ON THE OUTLOOK FOR THE SUPERSONIC VTOL-AIRPLANE

It might be attractive to examine what possibilities exist for the development of a truly high performance, i.e., supersonic VTOL airplane. Referring again to Figure C2, we note that only discrete singular approach alleys appear to exist. Indicated by arrows in the upper part of Figure C2, they are (a) the unloaded stored rotor, (b) the submerged fan and (c) direct jet thrust.

The unloaded rotor, of course, will have to be retracted and stored inside the fuselage for high speed flight. This implies either a fairly long fuselage (common in supersonic aircraft) or a rotor that is reduced in size (telescoped) before storage. It is evident that the mechanical difficulties are sizable. Nevertheless, this method may appear attractive because its low area loading makes sizable hovering times possible without too large penalties in fuel weight and range.

In the submerged fan solution, the lifting device being contained within the confines of the high speed configuration needs not to be changed for transition. However, it must be realized that high speed configurations tend to have small planforms and thin wings and, therefore, the problem of finding space for the submerged fan is quite difficult. This will tend to drive area loadings even higher than they are at present. The associated high exit velocities will require fields that are prepared for the operation of this kind of airplane and thus one of the most attractive features of the VTOL airplane, the ability to operate from unprepared fields, will be impaired.

The third possibility is the pure jet thrust airplane with enough jet engines or engines powerful enough to lift the airplane off vertically.

For the normal high speed operation, part of the engines may be shut down or they may be throttled. We have seen previously that this arrangement entails large penalties in dead weight and fuel consumed in the take-off maneuver. The erosion and ingestion problem will be most severe, and it is quite obvious that prepared fields will be required.

TABLE C1

B.II. VTOL AIRCRAFT

(F = Flown Successfully, * estimated)

				Area Loading lb/ft²	Power Loading lb/HP	Hovering Efficiency	Cruising Speed Knots	Downwash Velocity (Knots)	Gross Weight lb	Power plant
(a)	UNLOADED ROTOR AIRCRAFT									
	1. McDonnell XV-1	F	Unloaded Rotor	7.3	10	0.6	148	69	5,500	(1) Continental R 975-19 550 HP
	2. British Unloaded Rotor	F	Unloaded Rotor	6.14	7.5	.50	148	56	39,000	(2) Napier-Eland 2600 HP
(b)	TILTED ROTOR AIRCRAFT									
	3. Transcendental Model 2		Tilted Rotor	4.4	9	.5-.6	* 114	37	2,250	(1) Lycoming 0-435-23 250 HP
	4. Transcendental Model 1-G	F	Tilted Rotor	3.8	11-12	0.6	104	34	1,750	(1) 160 HP
	5. Bell XV-3	F	Tilted Rotor	10	8-10	.70	145	80	3,200	(1) Pratt & Whitney R985 450 HP
(c)	DEFLECTED SLIPSTREAM & TILTED ROTOR-PROPELLER & WING AIRCRAFT									
	6. Fairchild Model 224 (VZ-5FA)		Deflected Prop-Stream	18	4.0	-	140	74	3,976	(1) GE YT 58-GE-2 1000 HP
	7. Ryan Vertiplane (VZ-3RY)	F	Deflected prop-stream	20	3.4-3.8	.71	130	113	2,700	(1) Lycoming T-53 825 HP
	8. American Deflected Propeller Stream		Deflected prop-stream	* 31	* 3.5	* .5	* 150	* 95	* 2,400	(2) Lycoming GSO-480 340 HP
	9. Vertol 76 (VZ-2)	F	Tilted Rotor-prop+Wing	24	3.9-4.4	.61	130	85	3,200	(1) Lycoming T-53 825 HP
	10. Kaman K16		Tilted Rotor-prop+Wing	* 24.9	* 4.4	* .60	* 260	* 87	9,000	(2) GE T58-2A 1000 HP
	11. Hiller X18	F	Tilted Rotor-prop+Wing	* 82	* 2.8	* .74	* 230	* 157	33,000	(2) Allison T-40AA 14 5850 HP
(d)	SUBMERGED DUCTED FAN AIRCRAFT									
	12. American Submerged Fan		Prop. in wing	* 25	* 7	* .6	* 130	* 60	* 2,500	(1) 400 HP
(e)	TAILSITTER PROPELLER AIRCRAFT									
	13. Convair XFY-1	F	Tailsitter Prop.	70	2.4-3.0	.74	340 +	146	14,000	(1) Allison YT-40A 5850 HP
	14. Lockheed XFV-1	F	Tailsitter Prop.	* 70	* 2.4-3.0	* .74	* 340 +	* 146	* 14,000	(1) Allison YT-40A 5850 HP
(f)	TILTED DUCTED FAN AIRCRAFT									
	15. Doak 16 (VZ-4DA)	F	Tilted ducted prop.	95	3.8-4.2	.76	200	119	3,100	(1) Lycoming T-53 825 HP
(g)	JET AIRCRAFT									
	16. Bell Air Test Vehicle	F	Tilted Jet	310	* 2.2	-	-	214 +	2,000	(2) Fairchild J-44 1000 lb Static Thrust
	17. Bell X-14	F	Deflected Jet	480	* 2.0	-	139	267 +	3,000	(2) Armstrong-Siddeley Viper 1750 lb Static Thrust
	18. British Jet Lift	F	Jet in Aircraft	640	* 1.2	-	-	310 +	7,500	(5) Rolls-Royce RB-108 2010 lb Static Thrust
	19. Ryan X-13	F	Tailsitter Jet	800	* 1.2	-	* 375 +	343 +	7,500	(1) Rolls-Royce Avon 10,000 lb. Static Thrust
	20. French Ring Wing		Tailsitter Jet	875	* 1.1	-	* 350 +	356 +	6,175	(1) SNECMA Atar 101 EV 8155 lb Static Thrust

TABLE CII

B. III. AERIAL PLATFORMS OR JEEPS

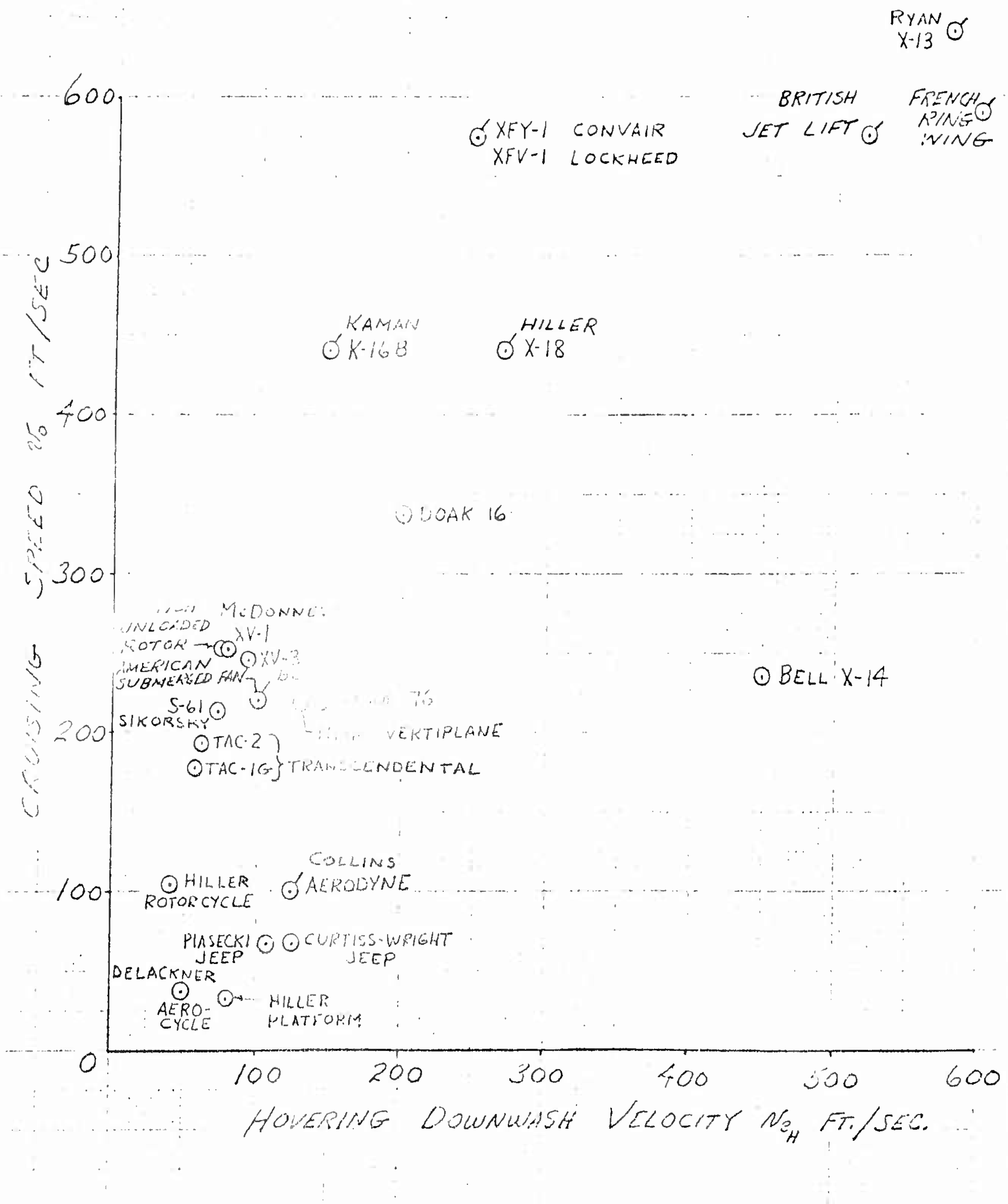
(F = Flown Successfully, * estimated)

				Gross weight lb	Area Loading lb/HP	Power Loading lb/HP	Hovering Efficiency	Maximum Speed, Knots	Downwash Velocity Knots	Power plant
1.	Hiller Platform	F	Ducted Propeller Stand-on Platform	555	14.7	6.6	.60	17	48	(2) Nelson H-56 40 HP
2.	DeLackner Aerocycle	F	Free Propeller Stand-on Platform	500	2.8	12.5	.55	22	29	(1) Kiekhaefer Mercury Mark 55 40 HP
3.	Piasecki Jeep (VZ-8P)	F	Tandem Ducted Propeller Jeep	2350	27	5.5	.60	39	63	(1) Turbomeca Artouste II B 425 HP
4.	Aerophysics Jeep (VZ-7AP)	F	Free Propeller (4) Jeep	2400	18	6.1	.69	39	73	(1) Turbomeca Artouste II B 425 HP
5.	Chrysler Jeep (VZ-6)	F	Tandem Ducted Propeller Jeep	2300	15	7	.6	39	47	(1) Lycoming GSO-480 340 HP
6.	Collins' Aerodyne		Ducted Prop. deflected slipstream vehicle	* 1600	* 36	* 3.75	* .6	* 60	* 73	(2) Continental 213 HP

FIG. C1

SUMMARY OF VTOL CRUISE AND HOVERING DOWNWASH VELOCITIES

NOTE: FLAGGED SYMBOLS INDICATE ESTIMATED DATA



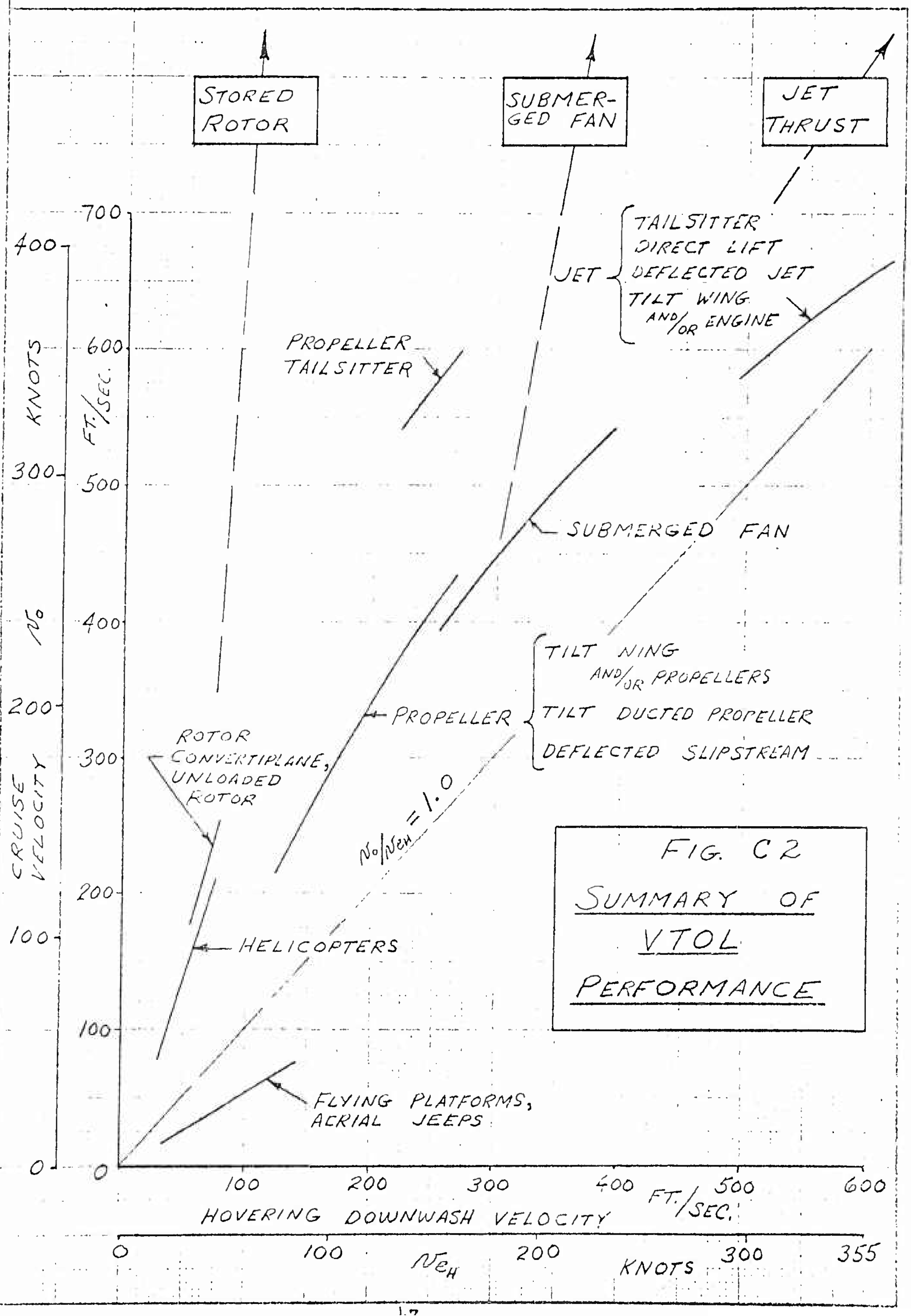


FIG. C2

SUMMARY OF VTOL PERFORMANCE

APPENDIX

VTOL AIRCRAFT

(a) UNLOADED ROTOR AIRCRAFT

1. McDONNELL XV-1

Configuration:

Unloaded rotor type helicopter - fixed wing combination. The 31 ft diameter rotor is tip driven by pressure jets. Two tail rotors 1' 3" diameter each.

Gross weight	5505 lb
Empty weight	4157 lb
Length	31.8 ft
Height	10.1 ft
Span	26 ft
Rotor diameter	31 ft
Solidity	9 percent
Rotor speeds	
helicopter flight	400 rpm
airplane flight	185 rpm
Area loading	7.3 lb/ft^2
Power loading	10 lb/hp
Hovering efficiency	0.7
Power plant (1) Continental R 975-19	550 hp

Control System:

Vertical flight

altitude	collective rotor pitch
pitch	longitudinal cyclic rotor pitch and elevator
roll	lateral cyclic rotor pitch and ailerons
yaw	(2) hydraulic tail fans and rudders

Forward flight

altitude	collective rotor pitch and tab operated free floating elevator
pitch	tab operated free floating elevator
roll	lateral cyclic rotor pitch and ailerons
yaw	rudders and tail fans

In addition, the XV-1 is equipped with a rotor speed governor to maintain constant rotor speed in forward flight. In forward flight, longitudinal cyclic control is disengaged and pitch control is obtained by means of the tab on the free floating elevator. The wing carries about 85% of the total weight during cruise flight, the remainder being borne by the rotor.

Performance:

Maximum cruise speed	148 knots
Normal cruise speed	120 knots
Rate of climb	1300 ft/min.

2. BRITISH UNLOADED ROTOR

Configuration:

Unloaded rotor type Helicopter - Fixed Wing combination. Rotor is 90' diameter, 4 bladed and driven by tip jets. 2 Napier Eland engines, mounted in wing pods, drive 2 variable pitch propellers and - through a hydraulic clutch - 2 air compressors. Wing with rotor pylon, engines and in-wing fuel tanks form integral unit to which fuselage under-carriage is attached. For VTO propellers are feathered and compressors engaged to supply air to tip jets where fuel (kerosene) is injected and burned. For transition, propeller pitch is increased and air compressors are disengaged leaving unloaded rotor auto rotating.

Gross weight	39,000 lb
Useful load	14,970 lb
Rotor diameter	90 ft
Rotor blade chord	2.25 ft
Number of blades	4
Wing area	475 ft^2
Propeller diameter	13 ft
Number of blades	4
Power plant (2) Napier Eland 6 engines	
max take-off	3150 HP
max continuous	2600 HP
cruise	2050 HP

Rotor power units (4) pressure jet units	
Length	58.75 ft
Span	46.5 ft
Height (to rotor head)	23.1 ft
Fuselage cross section	8 ft x 6 ft
Area loading	6.14 lb/ft^2
Power loading (max. continuous power)	7.5 lb/hp
Wing loading	82 lb/ft^2
Hovering efficiency	$\sim$ 0.5

Control System:

Vertical flight

altitude	collective rotor pitch
pitch	longitudinal cyclic rotor pitch
roll	lateral cyclic rotor pitch
yaw	differential propeller pitch and rudders

Forward flight

altitude	collective rotor pitch
pitch	longitudinal cyclic rotor pitch
roll	lateral cyclic rotor pitch
yaw	rudders

The control system is unique in that the control stick is used to operate only the cyclic rotor head, the ailerons and elevators being used for trim purposes only.

Performance:

Successful transitions have been performed. Claimed performance figures are:

Payload	10000 lb
Range	400 miles
Speed	170 miles/hr

The aircraft can fly with one engine only and still can achieve vertical climb with 3.3 ft/sec and full weight.

(b) TILTED ROTOR AIRCRAFT

3. TRANSCENDENTAL MODEL 2

Configuration:

Tilting-rotor convertiplane; a two-place single-engine monoplane with fixed tricycle landing gear. Two three-bladed rotors mounted on each wing-tip are interconnected and driven by the engine in the fuselage. Conversion to airplane flight is achieved by tilting the rotors to the propeller position.

Gross weight	2250 lbs
Useful load	670 lbs
Wing span	22.75 ft
Rotor diameter	18 ft
Number of blades	3
Area loading	4.4 lb/ft^2
Power loading	9 lb/hp
Hovering efficiency	0.5-0.6

Power plant: (1) Lycoming O-435-23, 250 hp

4. TRANSCENDENTAL MODEL 1-G

Configuration:

Tilting-rotor convertiplane; a conventional single-place single-engine monoplane with fixed tricycle landing gear. Two three-bladed rotors mounted on each wing tip are interconnected and driven by the engine located in the fuselage. To convert to the airplane mode, the rotors are tilted forward.

Gross weight	1750 lbs
Useful load	300 lbs
Rotor diameter	17 ft
Number of blades	3
Area loading	3.8 lb/ft^2
Power loading	11-12 lb/hp
Hovering efficiency	$\sim$0.6

Power plant: (1) 160 hp reciprocating engine

Performance:

The model 1-G has completed many conversions to airplane flight. Maximum speed is about 120 knots and cruising speed is slightly over 100 knots.

5. BELL XV-3

Configuration:

Research aircraft; Conventional single-engine monoplane with fixed skid-type landing gear. The engine is mounted in the fuselage and is connected through a two-speed gearbox to two 23 ft diameter rotors mounted on the wing tips. For hovering and low speed flight, the rotor thrust axes are held vertical. To accomplish transition to forward flight, the rotor thrust axes are tilted forward to a position parallel to the direction of flight and are thus used to propel the machine. When used in this manner, the rotor speed is decreased by means of the two-speed gearbox.

Gross weight	4600 lbs
Rotor - (semi articulated)	
diameter	23 ft
no. of blades	2
chord length	11 inches
twist	$18\frac{1}{2}^{o}$
Rotor tip speeds	
hovering gear ratio	640 ft/sec
airplane gear ratio	320 ft/sec
Power plant - 1 Pratt and Whitney	R 985
rated at 450 HP	

Control System:

Vertical flight

altitude	collective pitch
pitch	longitudinal cyclic pitch

yaw	differential longitudinal cyclic pitch
roll	differential collective pitch

Forward flight

conventional

Performance:

The XV-3 has demonstrated repeated conversions from helicopter to airplane flight with relative ease and efficiency. Hovering characteristics are similar to those of a helicopter. The aircraft control power is acceptable in pitch and roll but marginal in yaw with rather poor damping about all three axes. Both control power and damping improve as forward flight speed increases and conversion is begun. Longitudinal stick moves aft to increase angle of attack as the weight of the aircraft is transferred to the wing. Lateral stick remains nearly constant and rudder position is unchanged. Most of the increase in blade pitch angle is provided automatically by the conversion mechanism. Several conversions have been made holding longitudinal stick fixed, in which case the airspeed varies over about a 25 knot range. Conversion can be easily accomplished in a variety of different ways and can be stopped or reversed at any point. In the airplane configuration, handling characteristics are similar to those of airplanes with the exception that the longitudinal short period mode has marginal damping due to the destabilizing effect of the rotors.

Hovering test data showed a power loading of 11.2 lb/HP out of ground effect. This is equivalent to about 8.0 lb/installed HP because excess power must be provided for adequate altitude and hot-day performance. At the measured hovering value of 11.2 lb/HP and a disk loading of 5.55 lb/ft^2 the resulting Figure of Merit is 0.70.

Several wind tunnel test programs have been conducted by the NASA and AF on both the actual XV-3 and scale models to determine the propulsive efficiency of the rotors in propeller operation. The efficiency in helicopter gear ratio is about 50°/o at 132 knots. When the XV-3's two speed transmission is shifted to airplane gear ratio; the efficiency varied from 88°/o at 80 knots to about 70°/o at 145 knots. The XV-3 has relatively crude blade airfoils sections compared to those used on modern propellers. The maximum speed attained by the aircraft is about 145 knots. Vibration levels are low, however, noise levels are unusually high.

(c) DEFLECTED SLIPSTREAM & TILTED ROTOR - PROPELLER & WING AIRCRAFT

6. Fairchild Model 224 (VZ-5FA)

Configuration:

Research aircraft; conventional single engine high-wing monoplane with fixed tricycle landing gear. Four propellers mounted on the wing are interconnected and driven by an engine located in the fuselage. Large chord double-slotted wing flaps are used to deflect the propeller slipstream downward for vertical take-off and hovering flight.

Gross weight	3976 lbs
Useful load	594 lb
Overall length	33.75 ft
Span	32.7 ft
Height	16.8 ft
Propeller diameter	8.5 ft
Tail rotor diameter	2.75 ft
Fuel load	43.5 Gal
Wing loading	20.86 lb/ft^2
Power plant (1) GE YT58-GE-2 shaft turbine	1000 HP
Area loading	18 lb/ft^2
Power loading	4.0 lb/hp

Control System:

Vertical flight

altitude	collective propeller pitch
pitch	tail fan
roll	differential propeller pitch
yaw	tail fan

(c) DEFLECTED SLIPSTREAM & TILTED ROTOR - PROPELLER & WING AIRCRAFT

6. Fairchild Model 224 (VZ-5FA)

Configuration:

Research aircraft; conventional single engine high-wing monoplane with fixed tricycle landing gear. Four propellers mounted on the wing are interconnected and driven by an engine located in the fuselage. Large chord double-slotted wing flaps are used to deflect the propeller slipstream downward for vertical take-off and hovering flight.

Gross weight	3976 lbs
Useful load	594 lb
Overall length	33.75 ft
Span	32.7 ft
Height	16.8 ft
Propeller diameter	8.5 ft
Tail rotor diameter	2.75 ft
Fuel load	43.5 Gal
Wing loading	20.36 lb/ft^2
Power plant (1) GE YT58-GE-2 shaft turbine	1000 HP
Area loading	18 lb/ft^2
Power loading	4.0 lb/hp

Control System:

Vertical flight

altitude	collective propeller pitch
pitch	tail fan
roll	differential propeller pitch
yaw	tail fan

Forward flight

conventional

Performance:

The Fairchild aircraft is structurally limited to about 140 knots flight speed. It is currently undergoing wind tunnel tests at NASA Langley Field Research Center.

7. RYAN VERTIPLANE (VZ-3RY)

Configuration:

Conventional single-engine high-wing monoplane with fixed landing gear. Two propellers supported by pylons mounted on the wing are interconnected and driven by an engine located in the fuselage. Large chord double-slotted wing flaps and slots with end plates are used to deflect the propeller slipstream downward for vertical take-off and hovering flight.

Wing	
Area, sq ft	125
Span, ft	23.4
Aspect ratio	4.40
Taper ratio	1.0
Mean aerodynamic chord, ft	5.33
Sweepback, deg	0
Incidence, deg	22
Twist, deg	0
Airfoil section	NACA 4418
Flap	
Span of one flap, ft	10.0
Distance from fuselage center line to inboard end, ft	1.25
Chord	
Fore flap, ft	3.29
Aft flap, ft	3.05

Leading-edge slat	
Span of one slat, ft	10.0
Distance from fuselage center line to inboard end, ft	1.25
Chord, ft	1.67
Horizontal tail	
Area, sq ft	52.0
Span, ft	12.75
Aspect ratio	3.13
Taper ratio	1.0
Mean aerodynamic chord, ft	4.18
Sweepback, deg	0
Dihedral, deg	0
Tail length (wing $\bar{c}/4$ to tail $\bar{c}/4$)	13.76
Vertical tail, sq ft	18.8
Fuselage	
Length, ft	28.0
Frontal area, sq ft	13.3
Maximum width, ft	2.5
Engine	Lycoming T53
Propeller	3-bladed wooden Hartzell
Diameter, ft	9.167
Thrust axis inclination, relative to fuselage reference line, deg	13
Moments of inertia (weight = 2689 lb)	
I_X, slug-ft^2	1442
I_Y, slug-ft^2	2571
I_Z, slug-ft^2	3398
I_{XZ}, slug-ft^2	107

Area loading	20 lb/ft^2
Power loading	3.4-3.8 lb/hp

<u>Control System</u>:

Vertical flight

altitude	collective propeller pitch
pitch	turbine exhaust guide vanes at tail
yaw	turbine exhaust guide vanes at tail
roll	differential propeller pitch and spoiler-ailerons

Forward Flight

conventional

<u>Performance</u>:

The Vertiplane, through flight measurements and wind tunnel tests has been shown to be capable of controlled flight from zero to about 130 knots. Hovering could be accomplished with a 70° flap deflection when the thrust axis was inclined 35° and a thrust-to-weight ratio of 1.25 was applied. This performance required a total power input of about 700 HP which corresponds to a hovering Figure of Merit of 0.71. Propeller Figure of Merit is slightly higher, about 0.76 (excluding transmission losses). Forward flight propulsive efficiency (including transmission losses) reaches a peak value of 0.80 at blade pitch angles of 11.5°-20°. Maximum hovering efficiency occurred at a blade pitch of 11.5°.

Some stability and control difficulties exist which are similar to those problems encountered by most VTOL machines. Stick-fixed angle-of-attack instability exists for some flap deflections at speeds less than 42 knots. Increasing flap deflection at a given speed reduced this instability. This effect combined with weak pitch control produces marginal longitudinal handling qualities.

The lateral directional stability and control characteristics are not greatly affected by flap deflection at a given speed. The lateral control is marginal with only wing spoilers and is satisfactory with the spoilers in combination with differential propeller pitch.

8. AMERICAN DEFLECTED SLIPSTREAM

Configuration:

Operational prototype; four place high wing airplane powered by two 340 HP Lycoming GSO-480 reciprocating engines each driving a three blade propeller. It is equipped with a large chord sliding flap, a leading-edge slot, and wing tip fuel tanks which also serve as end plates. Approximate values for area loading and power loadings are 31 lb/ft^2 and 3.5 lb/hp respectively.

Performance:

The airplane has been flown in tethered hovering flight.

9. VERTOL 76 (VZ-2)

Configuration:

Conventional two-place high wing monoplane with fixed landing gear and a tilting wing-propeller assembly. Two propellers mounted on the wing are interconnected and driven by a single gas turbine mounted above the fuselage. The wing and propellers are rotated to the vertical position to provide VTOL capability.

Propellers:

Diameter, ft	9.5
Blade chord, in	13
Blade twist (linear, root to tip), deg	19.2
Airfoil section	NASA 0009 with 0.5-in. cusp
Blade taper ratio	1
Solidity	0.218
Distance between propeller axes, ft	14.67

Wing:

Span (excluding tips), ft	24.88
Chord, ft	4.75
Airfoil section	NACA 4415
Taper ratio	1
Sweep, deg	0
Dihedral, deg	0
Pivot, percent chord	37.6
Ailerons -	
Chord, ft	1.25
Span (maximum), ft	5
Tilt range (referenced to upper longeron), deg	9 to 85

Vertical tail:	
Height, ft	5.43
Chord (above rudder), ft	4
Sweep at leading edge, deg	0
Airfoil section	NACA 0012
Rudder -	
Chord (constant portion), in	21 $\frac{1}{2}$
Span (maximum), in	58
Horizontal tail:	
Span (less tips), ft	9.90
Chord, ft	3.00
Center section chord, ft	4.21
Sweep, deg	0
Airfoil section	NACA 0012
Dihedral, deg	0
Length (distance from wing pivot to leading edge of tail), ft	10.475
Hinge point (distance from leading edge), in	8.3
Control fans:	
Diameter (both fans), ft	2.00
Moment arm about wing pivot (both fans), ft	12.35
Number of blades	4
Fuselage length (approximate), ft	25.5
Engine	Lycoming T53
Weight as flown, lb	3,200
Empty weight	2,600

Center of gravity (for 9° wing incidence):	
Longitudinal[a], percent chord	32.5
Vertical, in. below wing pivot	~14
Center of gravity (for 85° wing incidence):	
Longitudinal[a], in. aft of pivot point	0.1
Vertical, in. below wing pivot	~11

[a]The longitudinal reference line is parallel to upper longeron.

Control System:

Vertical flight

Altitude	Collective propeller pitch
Pitch	Tail fan
Yaw	Tail fan
Roll	Differential propeller pitch

Forward flight

Conventional

Longitudinal control is obtained from an all-movable horizontal tail surface plus a tail fan capable of producing a pitching moment, and directional control is obtained from a conventional rudder plus a yaw fan. The blade angles of these fans are controlled by direct linkages with their related control surfaces. Differential propeller pitch supplies lateral control when the wing is in the hovering position, and conventional ailerons become effective when the wing is in the conventional forward-flight positions. A mechanism phases one lateral control in and the other out as the wing tilts through intermediate positions. The wing incidence control is actuated by the pilot by means of a push button. The pilot's primary power control is a helicopter-like collective pitch lever controlling the pitch of the two propellers. A governor holds the propeller speed constant at about 1410 RPM. The aircraft is equipped with pitch and roll rate dampers.

Performance:

Hovering efficiency	(excluding transmission losses)	0.66
Hovering efficiency	(including transmission losses)	0.61
Hovering area loading		24 lb/ft^2
Hovering downwash velocity		100 ft/sec
Forward speed		130 knots
Range		130 naut mi

The Vertol 76 aircraft is able to perform essentially continuous slow level-flight conversions with no major longitudinal trim changes. Studies have shown that the explanation of this ability lies in the shift with wing incidence of the curves of longitudinal stick trim position plotted against airspeed and the direction of the slopes of these curves at intermediate wing incidences. No large amount of transient longitudinal control was used other than rate-damper induced elevator motions during short-period oscillations. Prohibitive power variation, which would be reflected in the need for excessive pilot attention to propeller pitch control, was not noted.

10. KAMAN K-16 B

Configuration:

V/STOL flying boat research aircraft; conventional twin-engine high-wing monoplane using two prop-rotors mounted on a tiltable wing. The prop-rotors are interconnected and driven by two T-58 gas turbines mounted in the nacelles. The wings are provided with Fowler flaps and tip floats which maintain a horizontal attitude when the wing is tilted to the vertical position.

Overall length	38.3 ft
Span	34 ft
Height	20.7 ft
Gross weight	9000 lb
Prop-rotor diameter	15.16 ft
Number of blades	3

Rotation is in opposite directions being down at the wing-tips

Power plant (2) GE T-58-2A gas turbine engines

Area loading	24.9 lb/ft^2
Power loading	4.4 lb/hp
Hovering efficiency	$\sim$ 0.6

Control System:

Vertical Flight

Altitude	collective flap deflection
Pitch	longitudinal cyclic flap deflection
Roll	differential collective flap deflection
Yaw	differential longitudinal cyclic flap deflection

Forward flight

Conventional

The K-16 B control system features the Kaman servo-flap on the trailing edge of the rotor-prop blades. Primary pitch control in low-speed flight is achieved by the longitudinal cyclic flapping of the rotor-prop blades induced by cyclic blade flap deflection. A pitching moment is produced directly at the hub by virtue of the offset flapping hinges. In addition, a downward tilt of the thrust vector produces a downward component of thrust at the hub which is largely counteracted in vertical force by increased wing lift due to the increased wing angle of attack. Since there is a substantial horizontal separation between the rotor hub and wing aerodynamic center, however, these opposite and nearly equal vertical forces give rise to a couple which is in the pitching direction.

Performance:

The K-16 B is designed to fly at speeds ranging from zero to 200 knots. The aircraft program is currently entering the flight test stage.

11. HILLER X-18

Configuration:

Research V/STOL transport; conventional twin-engine high-wing monoplane with fixed tricycle landing gear. The engine-propeller-wing assembly tilts to the vertical position for hovering and low speed flight.

Gross weight	33000 lb
Span	48 ft
Length	63 ft
Height	24 ft
Propellers:	Curtiss Wright 16 ft, six-bladed counterrotating and interconnected
Power plant:	(2) Allison T-40 A 14 turboprops - 5850 HP each (1) Westinghouse J-34 turbojet
Area loading	82 lb/ft^2
Power loading	2.8 lb/hp
Hovering efficiency	$\sim$ 0.67

Control System:

Vertical flight

Altitude	collective pitch
Pitch	tail mounted turbojet with deflection vanes
Roll	differential collective pitch
Yaw	slipstream submerged ailerons

Forward flight

Conventional airplane controls

The X-18 is unique in its control design by employing airplane rather than helicopter type cockpit controls. The J-34 turbojet mounted in the tail is used for low speed control in pitch.

Performance:

Estimated cruising speed of the X-18 is about 220-260 knots. The aircraft is currently in the flight test stage.

(d) SUBMERGED DUCTED FAN AIRCRAFT

12. AMERICAN SUBMERGED FAN

A VTOL aircraft employing relatively lightly loaded fans in the wings to achieve vertical take-off. For conventional forward flight, metal lids cover the wing's upper surface and the aircraft is driven by a ducted propeller located at the tail. The landing gear is the tricycle type. A reciprocating engine in the fuselage drives the fans and propeller through a transmission and clutch arrangement. In transition, the slip-stream from the wing fans are deflected by a cascade of vanes on the lower part of the wing.

(e) TAILSITTER PROPELLER AIRCRAFT

13. CONVAIR XFY-1

Configuration:

Research aircraft, conventional propeller driven delta-wing tail sitter. Landing gear consists of oleo-legs mounted on the tips of the wings and vertical stabilizer.

Gross weight	14000 lb
Power plant: (1) Allison YT-40A Turboprop rated at	5850 HP
Propeller: Curtiss-Wright 16 ft diameter six bladed counter-rotating	
Area loading	70 lb/ft^2
Power loading	2.4-3.0 lb/hp
Hovering efficiency	$\sim$0.74

Elevon and rudder control surfaces located within the propeller slipstream provide control in both hovering and forward flight.

Performance:

The XFY-1 successfully completed six complete transition flights in 1954. The flight test program was terminated in 1956 because of difficulties encountered with the engine and propeller.

14. LOCKHEED XFV-1

Configuration:

Research aircraft, conventional propeller driven unswept tailsitter with cruciform tail surfaces. Landing gear consists of oleo-legs mounted on the tips of the tail surfaces.

Gross Weight	~14000 lb
Power plant: (1) Allison YT-40A turboprop rated at 5850 HP	
Propeller: Curtiss-Wright 16 ft diameter six-bladed counterrotating	
Area loading	70 lb/ft^2
Power loading	2.4-3.0 lb/hp
Hovering Figure of Merit	~0.74

Control System:

Tail control surfaces operating in the propeller slipstream provide roll, yaw, and pitch control in hovering and forward flight.

Performance

The airplane was equipped with a special fixed landing gear to permit conventional take-off and landing. Flight testing, which began in 1954, included many transitions made at altitude; but no vertical take-offs and landings were ever attempted. As in the case of the XFY-1, the project was terminated in 1956 because of engine and propeller difficulties.

(f) TILTED DUCTED FAN AIRCRAFT

15. DOAK 16 (VZ-4DA)

Configuration:

Conventional single-place mid-wing monoplane with fixed tricycle landing gear and tilting ducted fans mounted on each wing tip. Fans are interconnected and driven by a fuselage mounted engine. Thrust axes are rotated to the vertical position to provide VTOL capability.

Ducted propellers:	
Diameter, ft	4
Number of blades (each fan)	8
Ducts:	
Inside diameter, ft	4
Chord, ft	2.75
Rotation, deg	92
Wing:	
Span (excluding ducts), ft	16
Overall span, ft	25.3
Mean aerodynamic chord, ft	5.89
Airfoil section (modified)	NACA 2418
Taper ratio	0.747
Sweep, deg	0
Dihedral, deg	0
Area, sq ft	96
Area of each aileron, sq ft	6.2

Vertical tail:	
Height (approximate), ft	4.8
Average chord, ft	2.55
Airfoil section (modified)	NACA 0012
Area, sq ft	13.9
Horizontal tail:	
Area, sq ft	28.5
Airfoil section (modified)	NACA 0012
Span (projected)	11.6
Dihedral, deg	10
Fuselage length (approximate), ft	28.7
Overall length (approximate), ft	31
Engine	LYCOMING YT-53-L-1
Weight as flown (approximate), lb	3100
Center of gravity:	
Forward, percent M.A.C.	25
Rearward, percent M.A.C.	32

Control System:

Vertical flight

altitude	engine RPM control
pitch	turbine exhaust vane
yaw	turbine exhaust vane
roll	duct inlet guide vanes

Forward flight

conventional

The inlet guide vane roll control is phased out as the duct axes are rotated to the horizontal position so that lateral stick movements cause no guide vane deflection when the aircraft is flown in normal forward flight. Cruciform tail vanes in the engine-exhaust exit are used for pitch and yaw control in hovering. These cruciform tail vanes are not phased out as the duct axis are tilted forward. A long stainless steel tail pipe directs the turbine exhaust gases over the tail vanes. These vanes are of three-piece articulated design. Height control is accomplished in the hovering configuration by variation in rotational speed of the fixed pitch ducted fans. A vernier adjustment is provided for this purpose. The horizontal stabilizer can be varied through 11° to help offset the nose-up pitching moment encountered during conversions. Duct rotation control consists of a button on the control stick and rotation can be effected in a minimum time of 11 seconds.

Performance:

The airplane characteristics were investigated during three maneuvers: hovering and vertical ascent and descent, transition from hovering to forward flight and reverse.

1. Results obtained during conversion from hovering to forward flight indicate that this condition provides the most desirable flying qualities of the three conditions studied. The ducts were rotated to 0° continuously in the minimum amount of time, power changes were smooth, and the control deflections, although judged to be excessive, were not intolerable. The altitude against time curve shows a continuous increase throughout the accelerating

condition, indicating that the aircraft is capable of complete conversion during an uninterrupted climb-out from the take-off point.

2. The results obtained during conversion from forward flight to hovering indicate that this maneuver represents the largest problem area, insofar as the practical operational standards for transition flying are concerned. The most apparent of the difficulties encountered in this maneuver was the excessive longitudinal trim change caused by variation of aerodynamic moments acting on the duct. Action of the duct-induced downwash on the horizontal stabilizer also contributes to the longitudinal trim variations.

3. During hovering and vertical descent to landing, results indicated angular displacements of the aircraft of $\pm 10^{\circ}$ about the three axes. Plots of control positions show that as much as 50 to 60 percent of the total available control travel was used to control the aircraft during hovering in calm air.

Hovering fan efficiency	0.82
Hovering fan efficiency (including transmission losses)	0.76
Maximum forward flight propulsive efficiency	0.40
Exit area loading	95 lb/ft^2
Downwash velocity	200 ft/sec
Maximum speed	200 Knots
Fuel capacity	55 Gal
Fuel consumption	45 Gal/Hr

Range	230 naut. mi.
Rate of Climb (sea level)	4000 ft/min

(g) JET AIRCRAFT

16. BELL AIR TEST VEHICLE

This aircraft represents one of the earliest jet VTOL efforts in the United States. The machine was a conventional high-wing monoplane with a fixed skid-type landing gear. Two jet engines, one mounted on each side of the fuselage were used to obtain hovering lift and by tilting, forward flight propulsion. Control in hovering flight was provided by compressed air jets at the wing tips and tail.

Approximate gross weight	2000 lb
Power plants (2) Fairchild J-44 turbojets rated at 1000 lb thrust	

The vehicle has hovered successfully. It is not known whether transition flights were ever attempted.

17. BELL X-14

Configuration:

Research aircraft; Conventional twin engine monoplane with fixed tricycle landing gear. Two jet engines are horizontally mounted in the forward and lower part of the fuselage. Cascades are employed to turn the exhaust gases downward for vertical take-off.

Gross weight	3000 lb
Span	34 ft
Length	25 ft
Height	8 ft

Power plant - Two Armstrong - Siddeley, ASV-8
Viper Jet Engines rated at 1750 lb static thrust

Area loading	$\sim$ 480 lb/ft^2
Power loading	$\sim$ 2.0 lb/hp

Control System:

Vertical flight

altitude	engine throttle
pitch	tail jet using compressor bleed air
yaw	wing tip jet using compressor bleed air
roll	wing tip jet using compressor bleed air

Forward flight

conventional

Vertical flight is achieved by diverting the engine exhaust gases downward. This is accomplished by a two-vaned cascade system which is controlled by the pilot. The yaw and roll control functions were combined and located at each wing tip. It is then possible to maintain a continuous application of force in the downward direction whether the controls are operating or in neutral position.

Performance:

The cascade system is able to turn the engine exhaust flow through an angle of 90° with only a $6^\circ/o$ loss in thrust. The total hovering lift on a standard day is approximately 3100 lb ($T/W = 1.03$). In spite of this low value, vertical take-offs were easily initiated because of the high fuel consumption.

Free hovering flights were initiated in February of 1957 and the pilot was successful in sustaining the aircraft in the air on its first attempt. No automatic stabilizing device was used. Flight testing in the early part of 1958 was directed toward the transition regions gradually increasing the speed of the aircraft, so that the pilot could gain experience in the lift-off and transition to forward flight. Level flights were then undertaken wherein the thrust was brought to the vertical condition and transition to vertical landing was accomplished. These vertical landing tests were followed by progressive transitions from vertical take-off to level flight. In May 1958, the demonstration requirements for the X-14 were completed by executing a vertical take-off, a transition to level flight, a short period of level flight at about 140 knots followed by a transition to a vertical landing.

18. BRITISH JET LIFT

Configuration:

Research aircraft; delta wing without tailplane, and tricycle landing gear. Four lifting jet engines are mounted in the fuselage and a fifth jet engine mounted horizontally in the tail section is used for propulsion.

Gross weight	7500 lb
Span	23.5 ft
Length	24.5 ft
Power plants: (5) Rolls-Royce RB-108 turbojet rated at 2010 lb thrust	
Area loading	640 lb/ft^2
Power loading	1.2 lb/hp

Control System:

All five engines have a compressor bleed supplying high pressure air to a common duct which feeds air nozzles used for stability and control in hovering flight. These control nozzles are positioned at the wing tips nose, and tail. Emission of air from the nozzles is controlled by the pilot and the aircraft's electro hydraulic stabilization system. In addition, the lifting engines are gimbal mounted so that the thrust axis may be inclined forward or backward 30° from the vertical to aid transition. This aircraft is equipped with an auto stabilizer which provides control inputs either directly from the pilot, from a rate sensor about the pitch and roll axes, or from the combination of pitch and roll rate sensors and an attitude sensor, whichever is desired by the pilot

The system is triplicated in order to insure safety. Push buttons are used to select the lift engines thrust axis direction. The control stick is used conventionally to provide pitch and yaw moments and a "collective pitch" lever is used for lift engine control while a twist grip provides propulsive engine control. A separate conventional throttle lever controls the propulsive engine thrust in forward flight.

Performance:

This aircraft has been flown extensively in hovering flight and has recently completed a transition to forward flight. Numerous other flights with conventional take-offs and landings have been successful.

19. RYAN X-13

Configuration:

Research aircraft; single place tailless modified delta wing aircraft with a single triangular vertical fin and rudder, wing tip endplates and powered by a single turbojet engine of 10,000 lb thrust without afterburner. The primary landing gear consists of a large hook on the underside of the fuselage near the nose and two fuselage bumpers located one on each side of the fuselage aft of the center of gravity and projecting below the keel.

While on the ground, the aircraft is rested upon a trailer, the bed of which may be rotated to the vertical for take-offs and landings. A trapeze arrangement on the trailer bed in conjunction with the nose hook is used to "anchor" the aircraft to the trailer bed.

Gross weight	7500 lb
Length	24 ft
Span	21 ft
Height	15 ft
Power Plant - (1) Rolls Royce Avon Turbojet	
Maximum engine thrust (non-afterburning)	10,000 lb
Area loading	$\sim$ 800 lb/ft^2
Power loading	$\sim$ 1.1 lb/hp

Control System:

Vertical flight:

altitude	engine throttle
pitch	engine exhaust deflection
yaw	engine exhaust deflection

roll	wing tip air jets
Forward flight:	
pitch, roll	elevons
yaw	rudder

Additional features of the control system are: (1) a throttle vernier adjustment since smooth hovering control seldom demands more than $1^{o}/o$ change in engine speed; (2) disengaging mechanism for the hovering controls so that the conventional aerodynamic controls could be evaluated; (3) a seat rotation mechanism enabling the pilot to partly offset the fuselage tilt.

Performance:

The X-13 has successfully accomplished a full cycle of VTOL operation, i.e., hovering to forward flight and back again. A temporary tricycle landing gear was installed during the initial flight tests to effect take-off and landing in the normal manner while conventional flight characteristics were investigated. The landing gear was then removed and a temporary structure of tubing installed to allow "tail sitting" so the plane could be climbed, hovered and maneuvered in the vertical attitude. The first such flight was made in May 1956 followed by simulated "hook-ons" to a nylon rope stretched between two up-right steel towers. Another X-13 was also equipped with conventional landing gear and used to explore transition from medium speed conventional flight to hovering vertical flight at altitude. The first such demonstration was completed in November 1956. Then the landing gear on this plane was removed and the nose-hook installed to permit take-off and landing on the trapeze of the ground service trailer. The flight demonstrating the full cycle of VTOL operation took place in April, 1957, using the ground service trailer.

20. FRENCH RING WING

Configuration:

A single-place, single engine tail sitter with an annular wing surrounding the fuselage. Cruciform fins are located at the trailing edge and a fuselage mounted turbojet with side inlets is used to power the craft. Landing gear consists of four oleo-pneumatic legs mounted on the trailing edge of the wing with small castering wheels.

Wing diameter	10.5 ft
Overall length	26.25 ft
Wing chord	9.83 ft
Gross weight	6175 lb

Power plant - (1) SNECMA ATAR 101 EV turbojet rated at 3155 lb static thrust

Thrust-to-weight ratio	1.32
Disc loading	$\sim$ 875 lb/ft^2
Power loading	$\sim$ 1.1 lb/hp

Control System:

Vertical flight

jet deflection nozzle

Forward flight

cruciform tail surfaces

Performance:

Two prototypes have been flown in hovering and low speed flight. They were essentially "flying engines", one of which was remotely controlled from the ground, the other employing a cockpit mounted atop the engine and controlled by a pilot. No details on the performance are available.

AERIAL PLATFORMS AND JEEPS

1. HILLER FLYING PLATFORM

Configuration:

Research aircraft, ducted propeller stand-on platform. Capable of sustaining one person and utilizing the "kinesthetic" type of control.

Gross Weight	555 lb
Propeller diameter	7 ft
Number of blades (2 counter-rotating)	2
Power plant: (2) Nelson H-56 aircooled reciprocating engines rated at 42 HP	
Area loading	14.7 lb/ft^2
Power loading	6.6 lb/hp
Hovering efficiency	0.60

Method of Control:

This vehicle is unique in that its control system uses only a throttle for altitude and a differential torque control for yaw. Pitch and roll control, consequently translation, is obtained solely from a moment obtained by shifting the pilot's weight on the platform. In addition, vanes placed in the slipstream at the duct exit are linked to a gyro-bar. This latter system provides increased pitch and roll damping.

Performance:

The Hiller vehicle has flown successfully in hovering and forward flight up to speeds of about 15 knots, and altitudes of nearly 100 feet. A remarkable photograph of this vehicle is available which shows it hovering at an altitude of about 75 ft with the operator using both hands to aim a rifle. Kinesthetic control makes use of the natural righting moments which enable a human to stand. These moments, coupled with the dynamic characteristics of the platform itself (which consist mostly of negatively damped oscillations) produce a stable system that is easy to fly. The major difficulty encountered during flight testing was a lack of trim moment available (through pilot weight shift) to balance the high nose-up moments experienced by the duct in forward flight. Later designs of this vehicle have incorporated an 8 ft. diameter duct, three engines and a raised center-of-gravity.

2. DELACKNER AEROCYCLE

Configuration:

Research aircraft, single place, stand on rotor platform utilizing kinesthetic control.

Gross weight	500 lb
Rotor diameter	15 ft
Number of blades	2
Two rotors - counterrotating with rigid blades	
Power plant: (1) Kiekhaefer Mercury Mark 55 engine rated at 40 HP	
Area loading	2.8 lb/ft^2
Power loading	12.5 lb/hp
Hovering efficiency	0.55

Method of Control:

The method of control is similar to that used in the Hiller platform. Throttle for altitude control, differential torque control for yaw and pilot lean for pitch and roll, or translation.

Performance:

The aerocycle has been flight tested extensively by the contractor, the US Army and by Princeton University. The major difficulties encountered were lack of available trim moment in forward flight and excessive blade deflections. Hovering flights have been made as well as low speed translations.

3. PIASECKI AIR JEEP (VZ-8P)

Configuration:

Research aircraft; tandem ducted rotor with central platform supporting the crew and cargo. Landing gear consists of four unpowered wheels mounted two on a side similar to an automobile.

Gross weight	2350 lb
Length	26 ft
Width	9.5 ft
Height	6.75 ft
Rotor diameter	7.5 ft
Number of blades	3
Power plant:(1) Turbomeca Artouste II shaft turbine rated at 425 HP	
Area loading	27 lb/ft^2
Power loading	5.5 lb/hp
Hovering efficiency	0.6

Control System:

Longitudinal control consists of longitudinal cyclic pitch plus differential collective pitch; roll control is obtained with lateral cyclic pitch plus duct exit vanes. Directional control is also provided by differentially actuating the lateral duct exit vanes. Collective rotor pitch and throttle are used for altitude control.

Performance:

The Air jeep has flown successfully in hovering and low speed forward flight. Control could be maintained although no artificial stabilization was incorporated. Some problems encountered with ducted craft of this type are excessive nose-down attitude required for trim, large nose-up moments caused by the ducts and stick-fixed unstable dynamic responses requiring more pilot skill.

4. CURTISS-WRIGHT (AEROPHYSICS) JEEP (VZ-7AP)

Configuration:

Research aircraft, quad-rotor with a centrally located platform for the engine, cargo and passengers. Conventional unpowered tricycle landing gear.

Gross weight	2400 lb
Useful load	600 lb
Length	18.2 ft
Width	9.7 ft
Height	7.6 ft
Rotor diameter	6 ft
Number of blades	2
Power plant: (1) Turbomeca Artouste II B rated at 425 HP	
Area loading	18 lb/ft^2
Power loading	6.1 lb/hp
Hovering efficiency	0.69

Control System:

altitude	collective propeller pitch
pitch	longitudinal differential propeller pitch
roll	lateral differential pitch
yaw	turbine exhaust vane

The rotors are semi-articulated and driven by right angle gear-boxes and an X shafting system.

Performance:

The Aerophysics Jeep has flown successfully both in hovering and forward flight at speeds of up to 40 knots. Control is excellent although the machine is inherently unstable hands-off. Only moderate tilt angles are required in forward flight and nose up moments are also small. No stability augmentors are required.

5. CHRYSLER JEEP (VZ-6)

Configuration:

Research aircraft; tandem ducted fixed pitch propellers with central platform supporting the engine, crew and cargo. Landing gear consists of four unpowered castering wheels.

Gross weight	2300 lb
Length	23.5 ft
Width	12.5 ft
Height	6.25 ft
Propeller diameter	8.5 ft
Number of blades	3
Power plant:(1) Lycoming GSO-480	340 HP
Exit area loading	15 lb/ft
Power loading	7 lb/hp
Hovering efficiency	0.6

Control System:

altitude	engine speed control (throttle)
pitch	duct inlet vanes
roll	duct exit vanes
yaw	duct exit vanes

In addition, the Chrysler jeep is equipped with an exit cascade in the front duct which is actuated by a button on the control stick. It is used to reduce the nose down tilt and the nose down trim moments required in such a vehicle.

Performance:

The Chrysler Jeep was designed to fly at speeds of up to 40 knots. It has flown in tethered hovering flight for short periods. The vehicle exhibited instability about all axes. An automatic stabilization system was found necessary however, control system weakness and non-linearities coupled with stabilization system difficulties rendered the machine unflyable.

6. COLLINS AERODYNE

Configuration:

Research aircraft: wingless ducted propeller deflected slipstream type with jet augmented conventional tail surfaces. Two reciprocating engines are mounted in tandem, each driving a two-bladed propeller. Both are contained in an annular - shaped fuselage. A cascade of vanes is placed within the fuselage just aft of the rear propeller which deflects the propeller flow downward for vertical take-off. A small portion of this flow is allowed to flow through the rear part of the fuselage and out a nozzle over the elevator.

The aerodyne itself has not flown; however, models have been flown successfully, and detailed wind-tunnel studies of the full-scale Aerodyne have been made by NASA.

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2. Vertical Take-off Planes

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II. Lange, A.H.
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